Fermilab U.S. DEPARTMENT OF ENERGY Office of Science

Neutrinos Knocking out Neutrons: The ANNIE Experiment

Steven Gardiner for the ANNIE Collaboration

Fermilab Neutrino Seminar
15 November 2018

annie

What is ANNIE?

The **A**ccelerator **N**eutrino **N**eutron **I**nteraction **E**xperiment

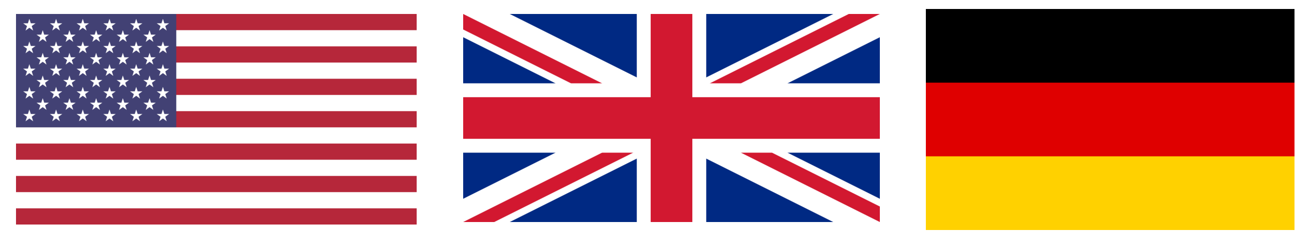
Concept drawing of the ANNIE detector

- Gadolinium-loaded water Cherenkov neutrino experiment on the Booster Neutrino Beam
- Measure the multiplicity of final-state neutrons from neutrino-nucleus interactions in water
- Demonstrate new detection technologies (fast photosensors, detection media)
- Background data taking complete (Phase I)
- Physics data coming soon (Phase II funded and under construction!)

The ANNIE Collaboration

Brookhaven National Laboratory
Fermi National Accelerator Laboratory
Iowa State University
Johannes Gutenberg University Mainz
Lawrence Livermore National Laboratory
Queen Mary University
The Ohio State University
University of California, Davis
University of California, Irvine
University of Chicago
University of Edinburgh
University of Hamburg
University of Sheffield

12 Institutions
3 Countries
~30 Collaborators



The ANNIE Collaboration

A few recent additions to the collaboration . . .

Where does ANNIE live?

Where does ANNIE live?

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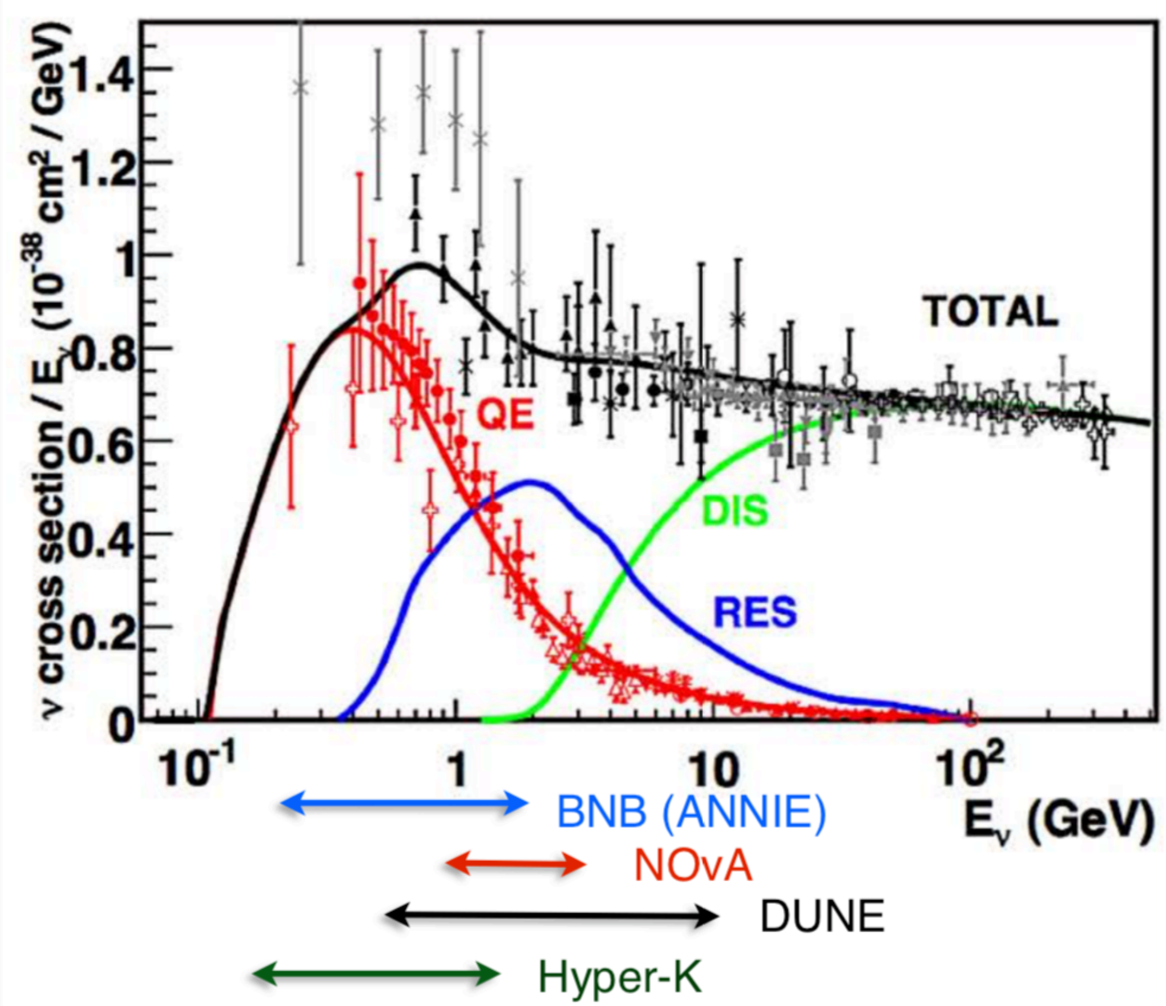
Physics Motivation

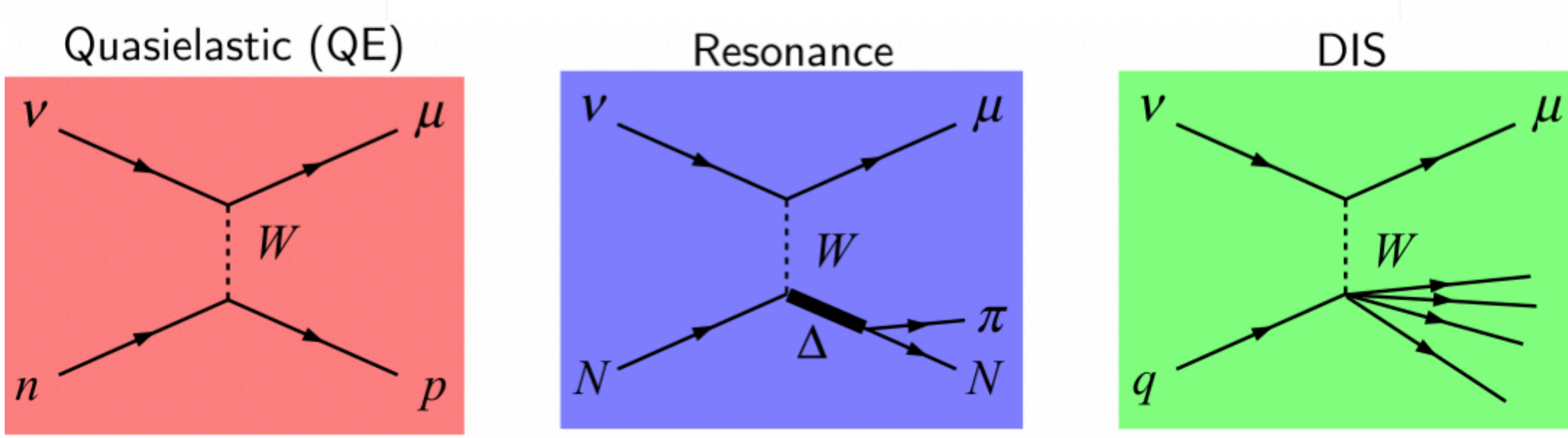
Why study neutrino-induced neutron production?

Physics with accelerator neutrinos

- Neutrino oscillation measurements can provide answers to lots of exciting questions
  - Leptonic CP violation
  - Neutrino mass hierarchy
  - Sterile neutrinos
- Accurate neutrino energy reconstruction needed for all of these efforts!

J. A. Formaggio and G. P. Zeller
Rev. Mod. Phys. 84, 1307 (2012)





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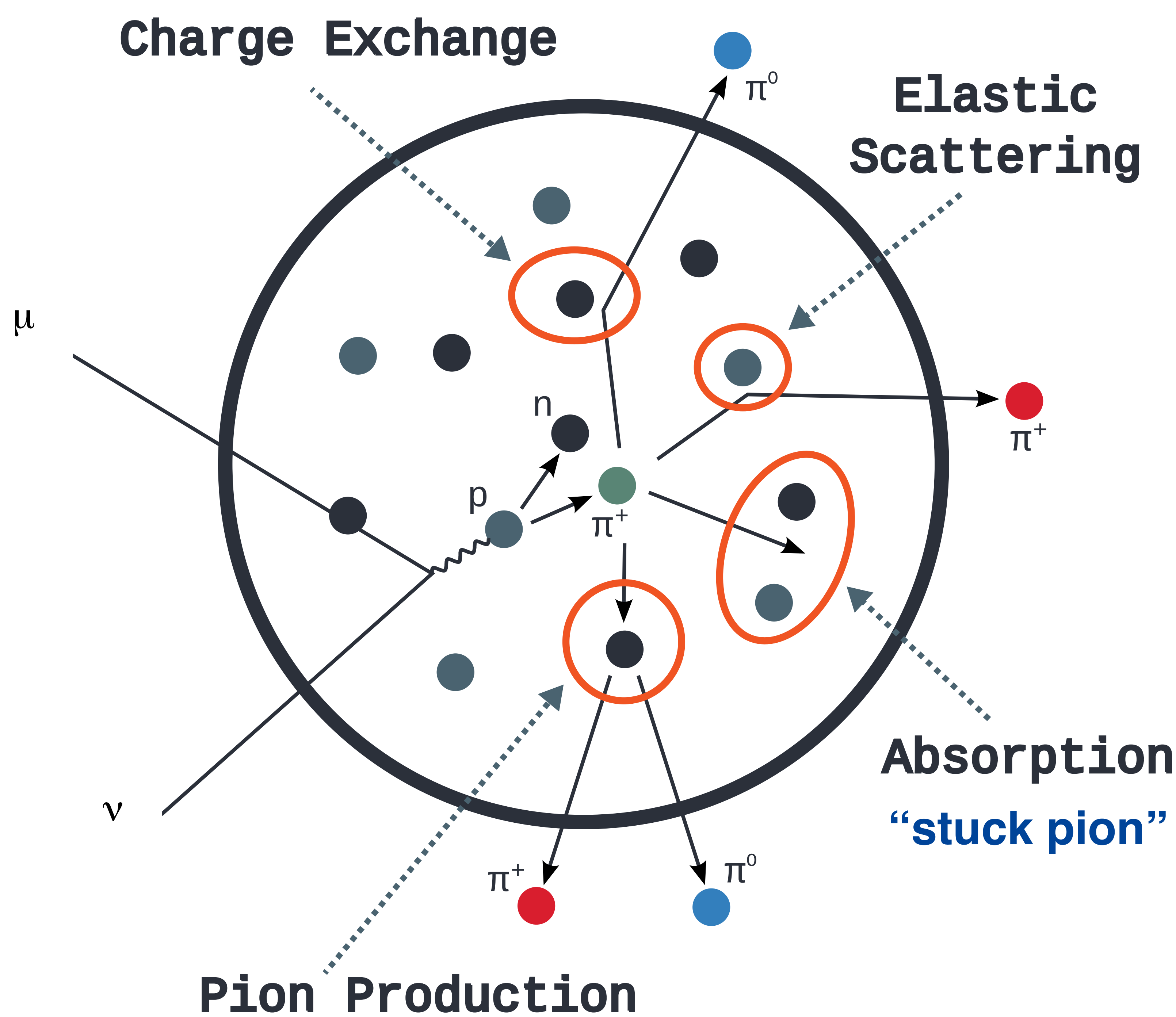
Nuclear effects complicate this simple picture

- **Correlations between nucleons** and **intranuclear rescattering** can obscure the true nature of the primary neutrino interaction

- Experimentalists must therefore rely on topological categories (e.g., 1μ + 0π rather than CCQE)



L. Alvarez-Ruso et al., *Prog. Part. Nucl. Phys.* 100, 1–68 (2018)

Neutrino energy reconstruction

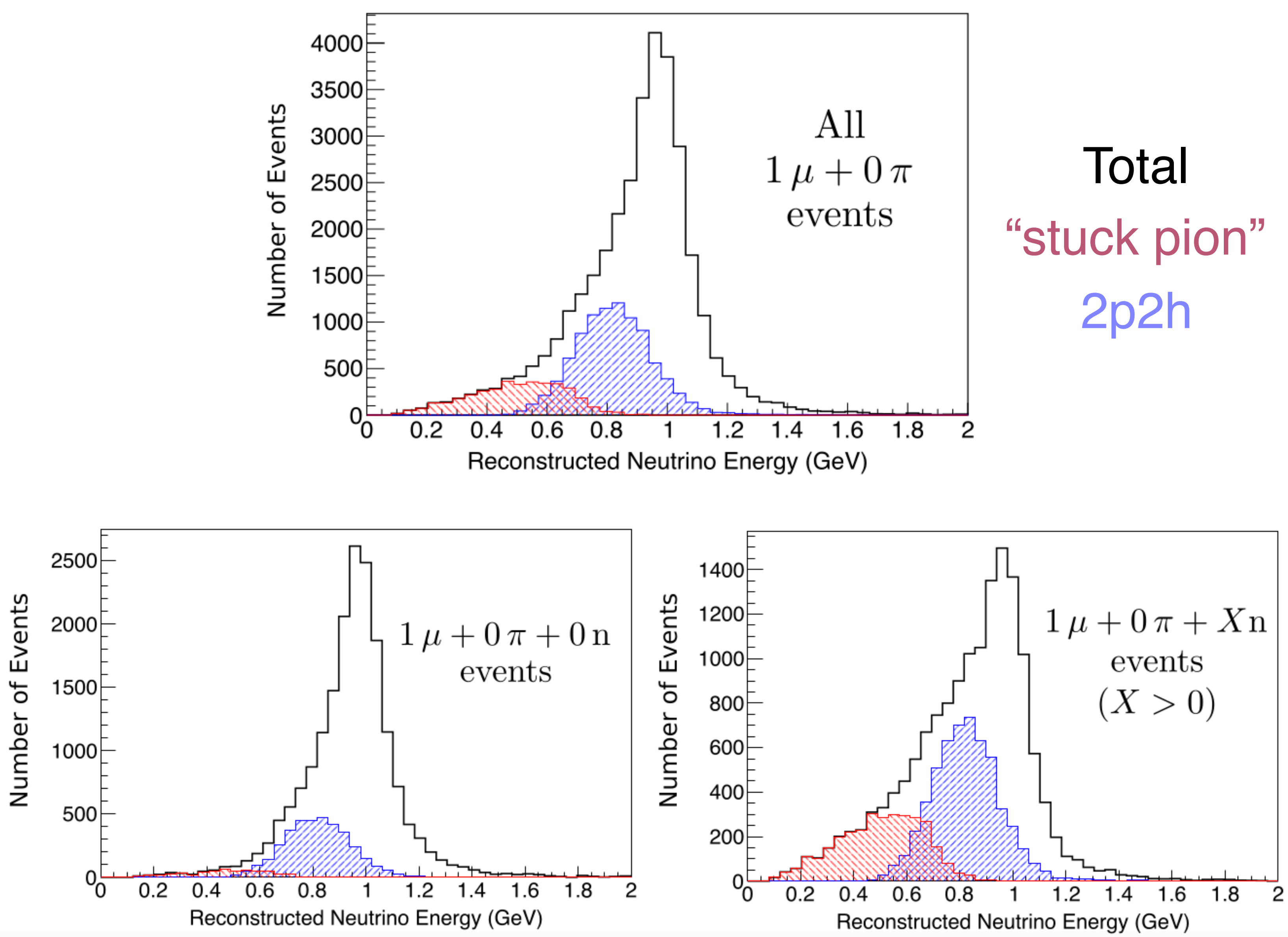
- Event generators are routinely used to correct for biases in the reconstructed neutrino energy

- Stuck pion and two-particle two-hole (2p2h) events significantly contaminate a CCQE-like $1\mu + 0\pi$ sample

- GENIE simulations suggest that neutron tagging can help improve the energy reconstruction

GENIE simulations of

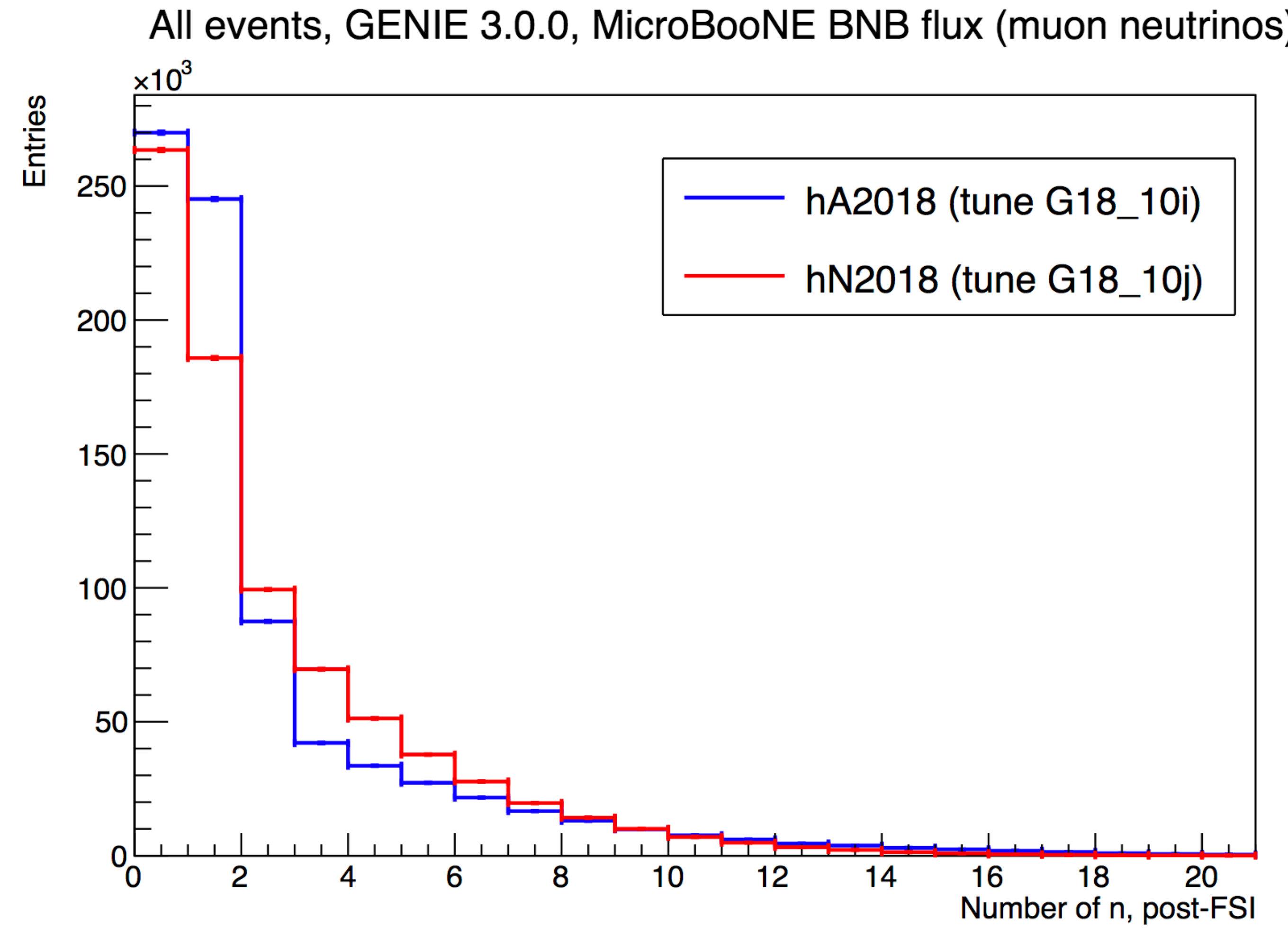
1 GeV ν_μ scattering in water



Nucleon yield uncertainties in generators

- Generators are an important but imperfect tool. Many theoretical challenges remain.
- **Nucleon yield predictions vary widely!**
- New data will help to constrain these models

GENIE v3.0 neutron yield prediction for a ^{40}Ar target



Red and **blue** histograms show results obtained using different final state interaction models

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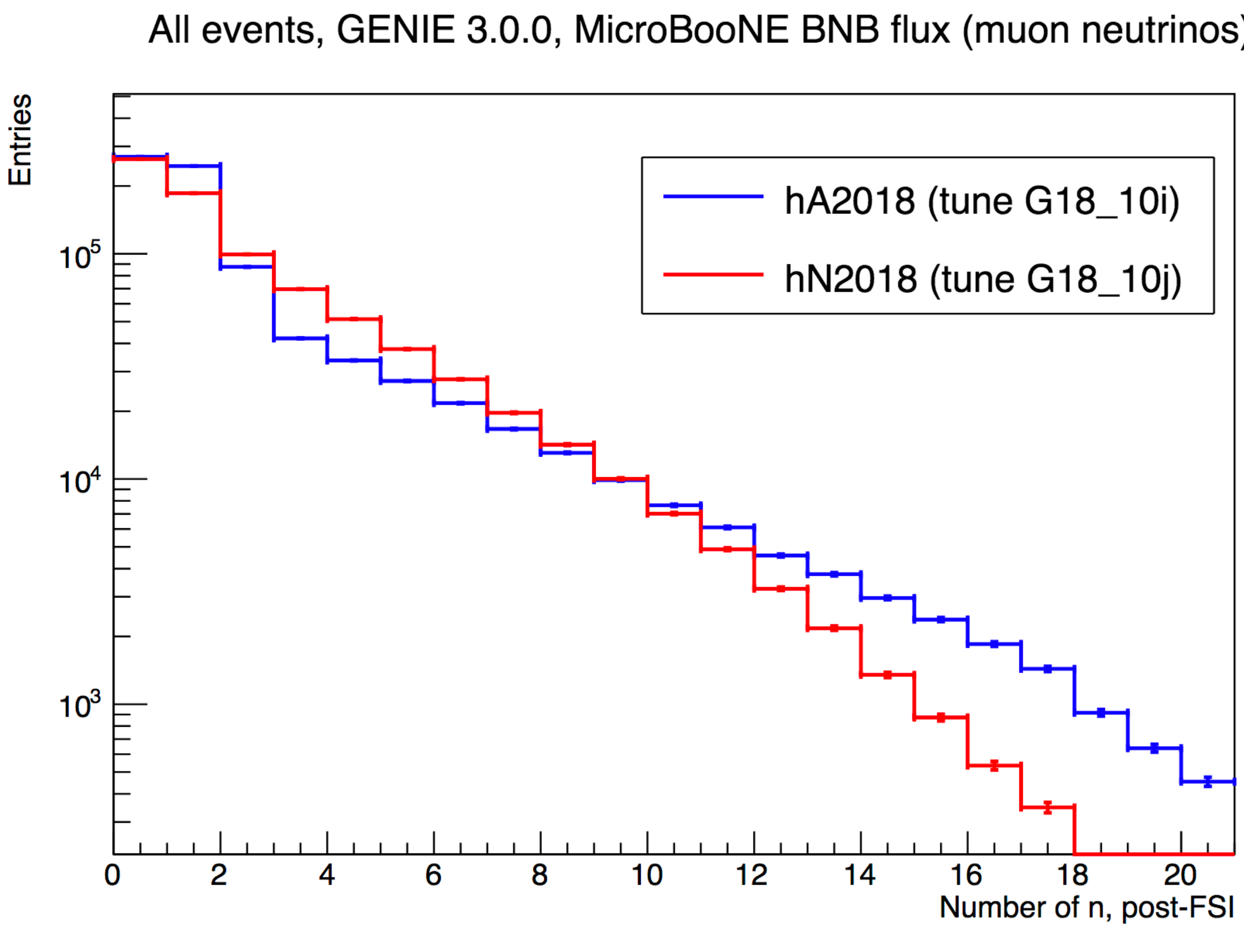

Red and blue histograms show results obtained using different final state interaction models

LArTPCs & Water Cherenkov detectors: complementary tools

- Liquid argon time projection chambers are a wonderful technology, but they **cannot give us a full picture of ν-induced nucleon yields on their own**
  - Proton multiplicity & energy, but with a high threshold (~50 MeV)
- **ANNIE will provide complementary information**
  - Total neutron yield down to the lowest energies

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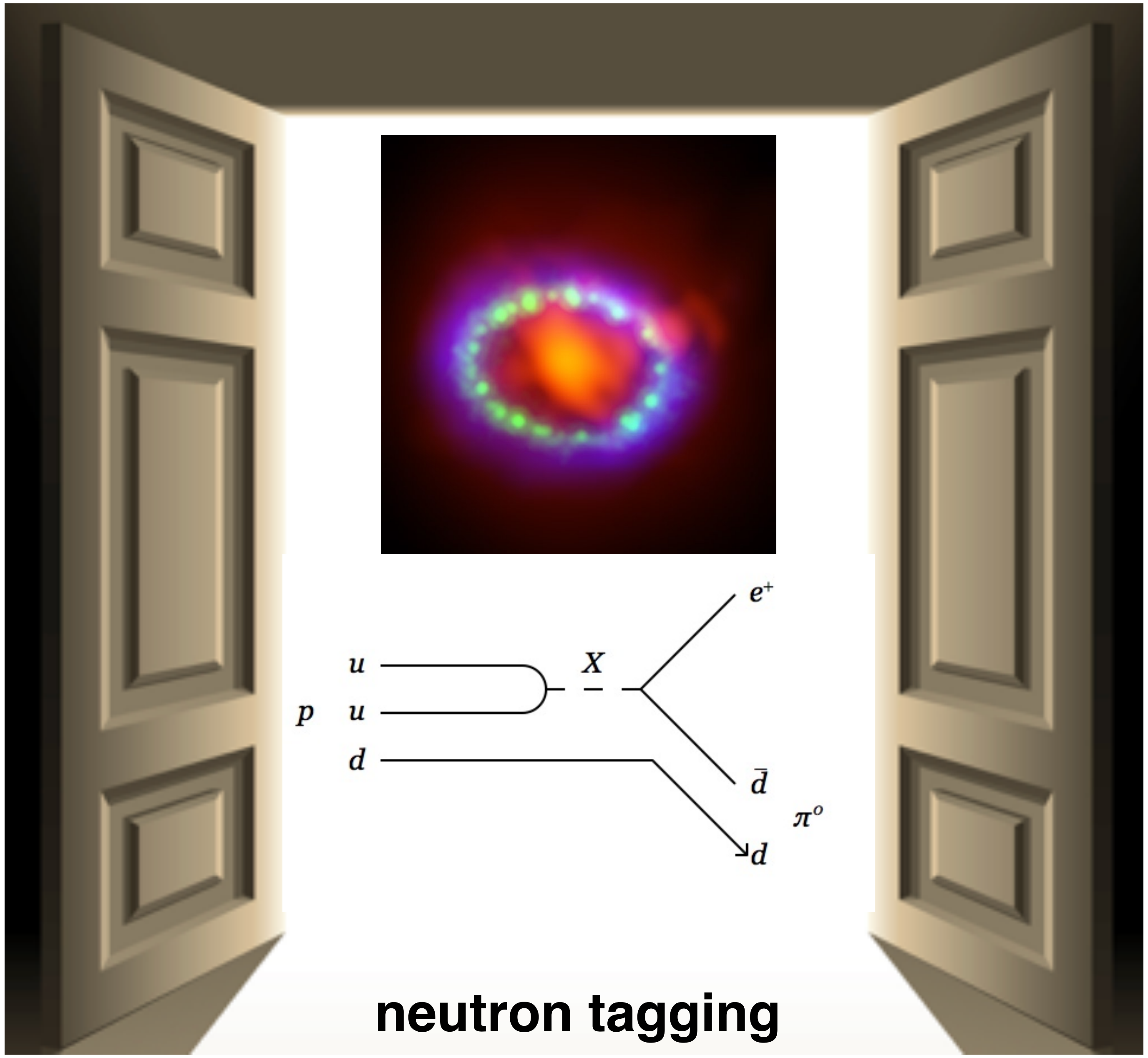
Neutron tagging for signal/background separation

- In addition to its relevance for oscillation physics, neutron tagging is a powerful tool to reduce backgrounds in rare event searches

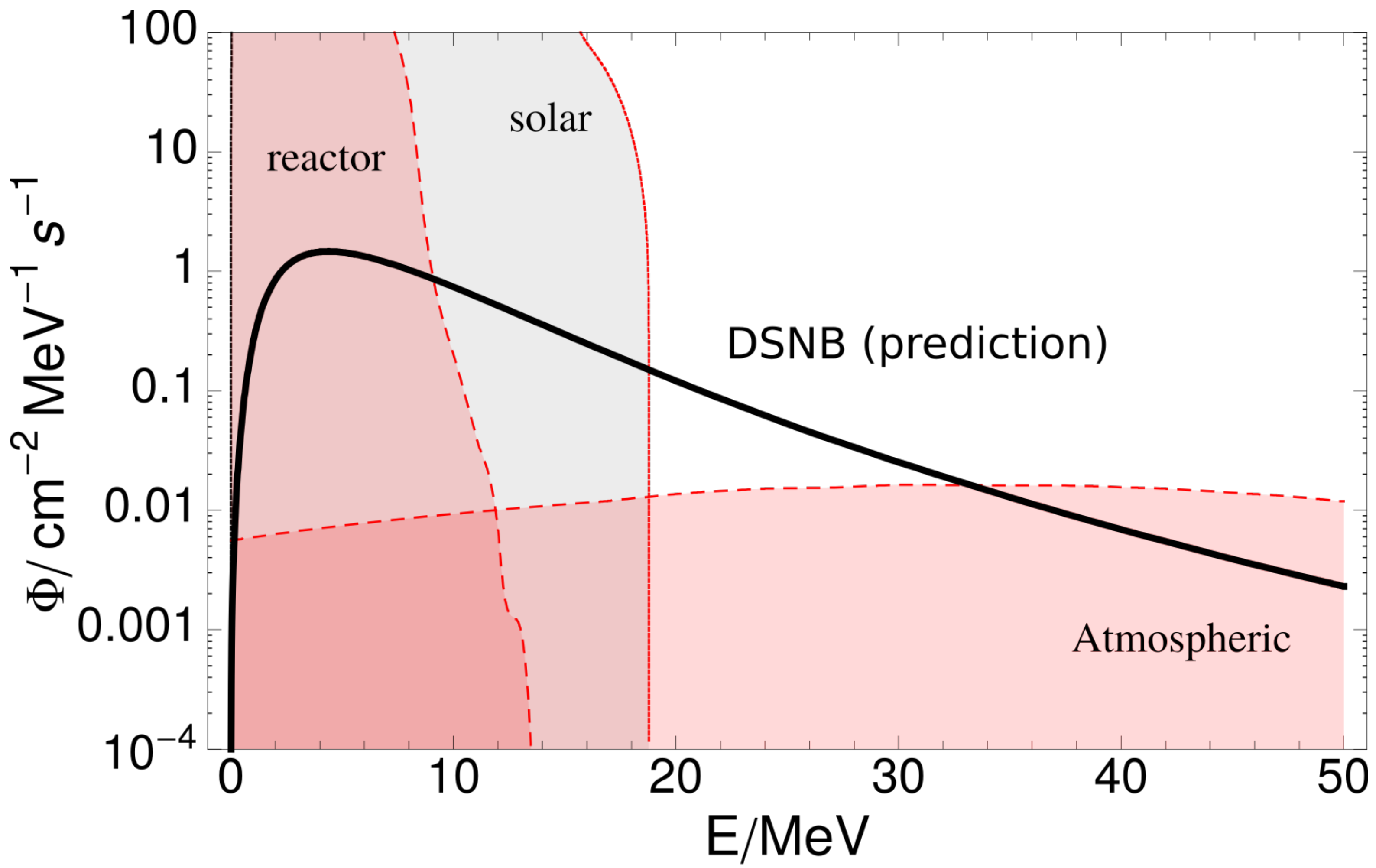
- **Super-Kamiokande will soon undergo a major upgrade, SuperK-Gd, to improve its neutron sensitivity**

- Example physics motivations
  - Supernova neutrinos
  - Proton decay searches



The Diffuse Supernova Neutrino Background (DSNB)

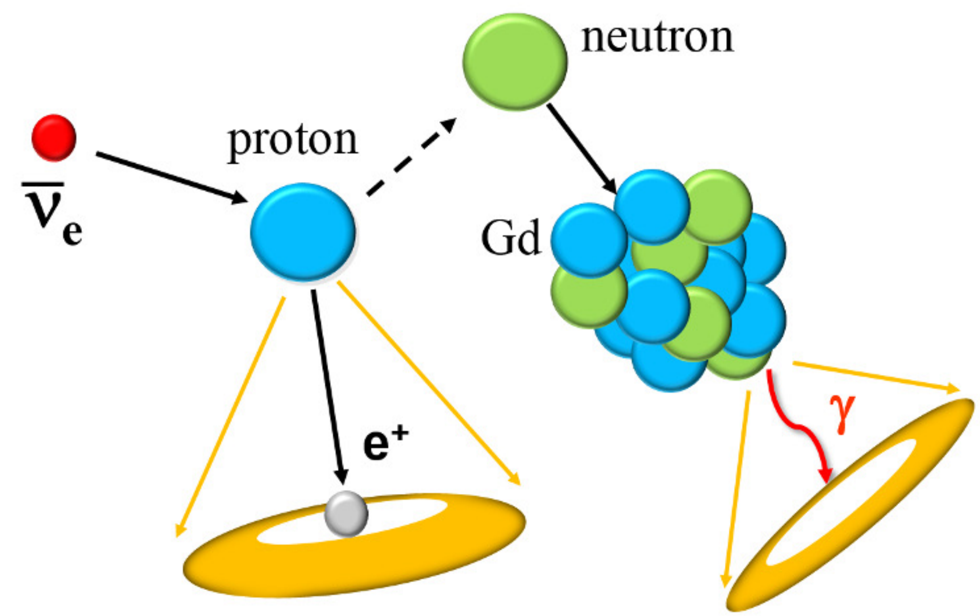
- Accumulation of all past supernova neutrinos
- Well-motivated, but **never experimentally observed**
- **Challenging because of significant backgrounds**
- Measurement would provide information about supernova rate, fraction that form black holes, average spectrum, etc.
- A small but steady source of supernova neutrinos



Based on Phys. Rev. D **85**, 043011 (2012)

Neutron tagging can aid the search for the DSNB

- Dominant background for diffuse supernova neutrinos above 20 MeV: decays of sub-Cherenkov muons produced by atmospheric neutrinos

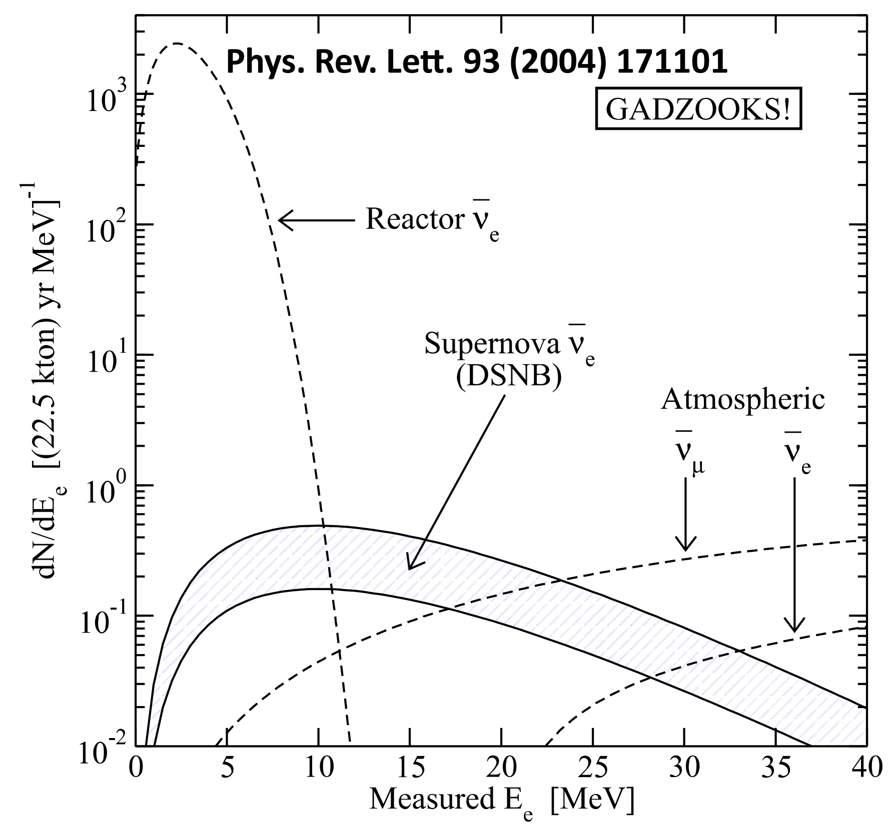


$$\mu^- \longrightarrow e^- + \bar{\nu}_e + \nu_\mu$$

$$\mu^+ \longrightarrow e^+ + \nu_e + \bar{\nu}_\mu$$

- These decays do **not involve neutrons**, so Gd captures can be used to distinguish signal from background

Predicted DSNB event rate in a Gd-loaded water Cherenkov detector



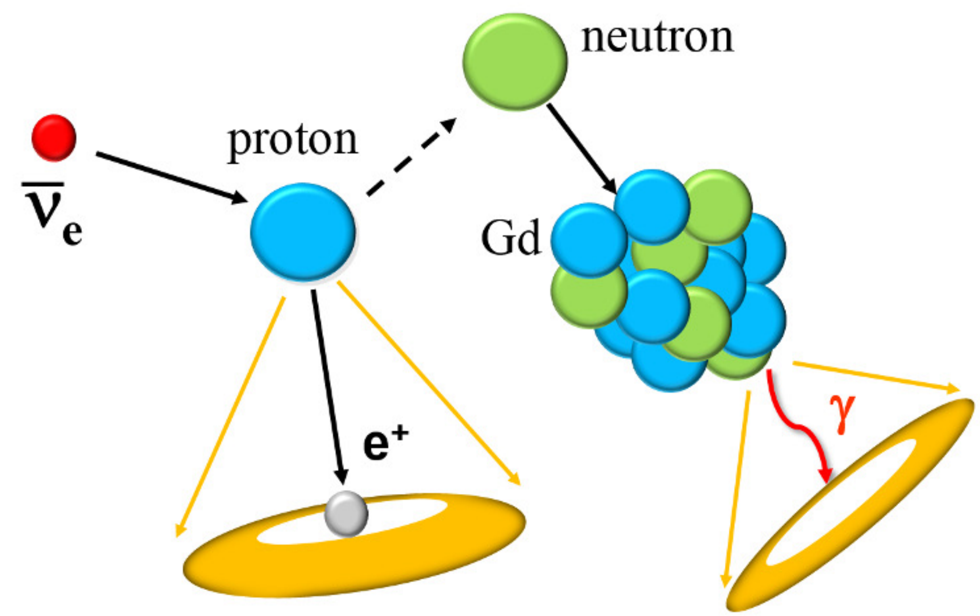
Neutron tagging can aid the search for the DSNB

- Dominant background for diffuse supernova neutrinos above 20 MeV: decays of sub-Cherenkov muons produced by atmospheric neutrinos

$$\mu^- \longrightarrow e^- + \bar{\nu}_e + \nu_\mu$$

$$\mu^+ \longrightarrow e^+ + \nu_e + \bar{\nu}_\mu$$

- **Caveat: neutron yields from atmospheric neutrinos are poorly understood**



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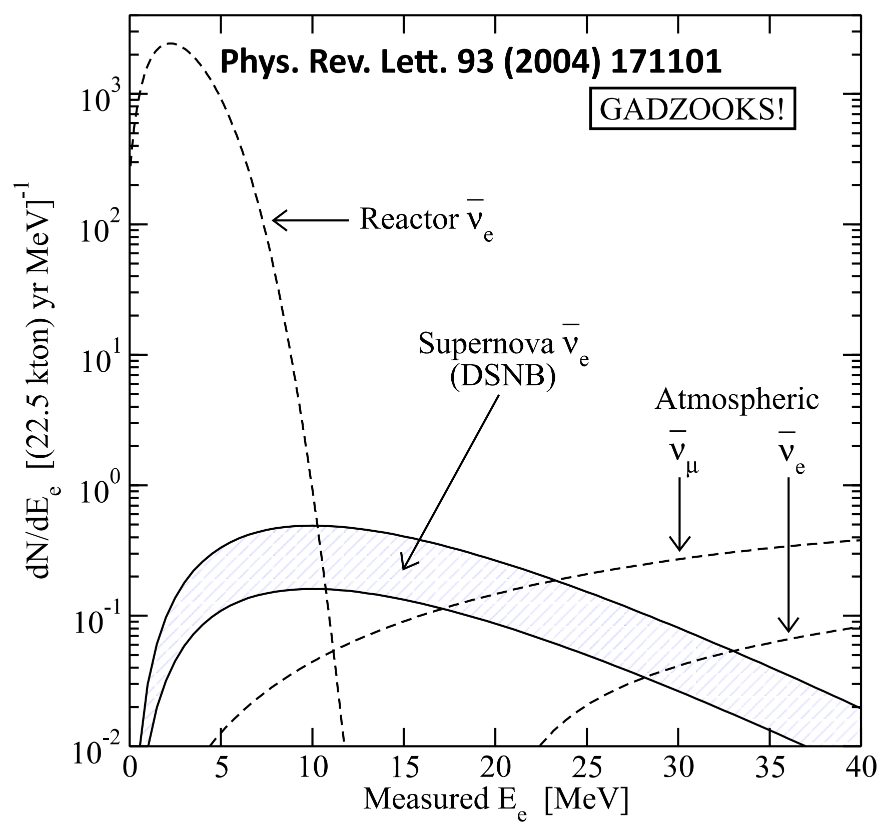
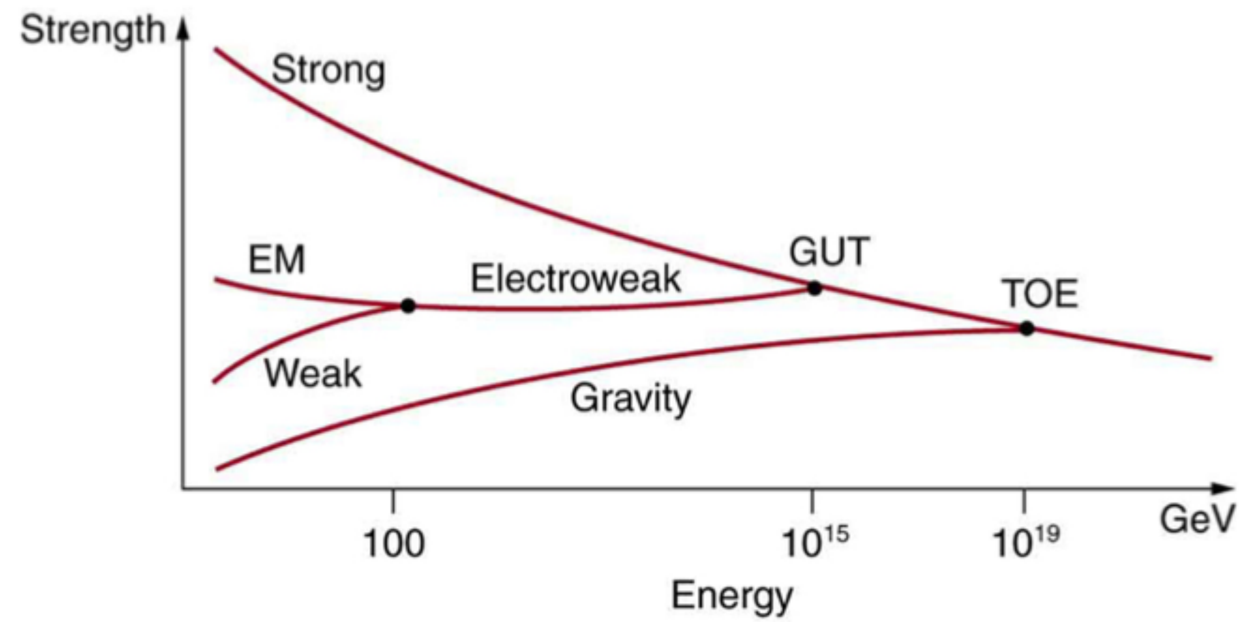


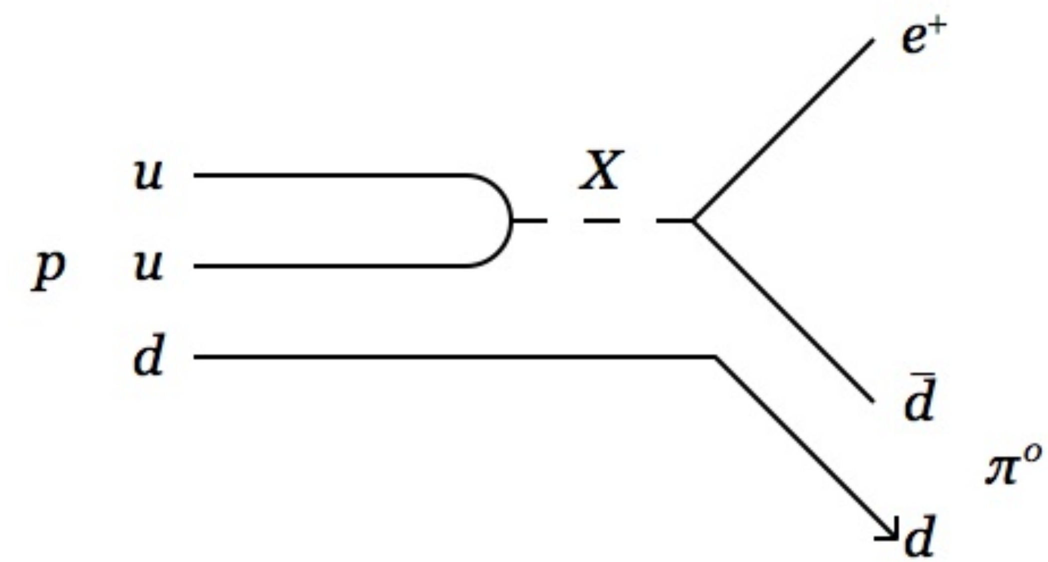
Proton decay: Is normal matter stable?



- Proton decays are a generic prediction of Grand Unified Theories

- Means of experimentally accessing a very high energy scale

$$\tau \approx \frac{M_X^4}{\alpha^2 M_p^5}$$



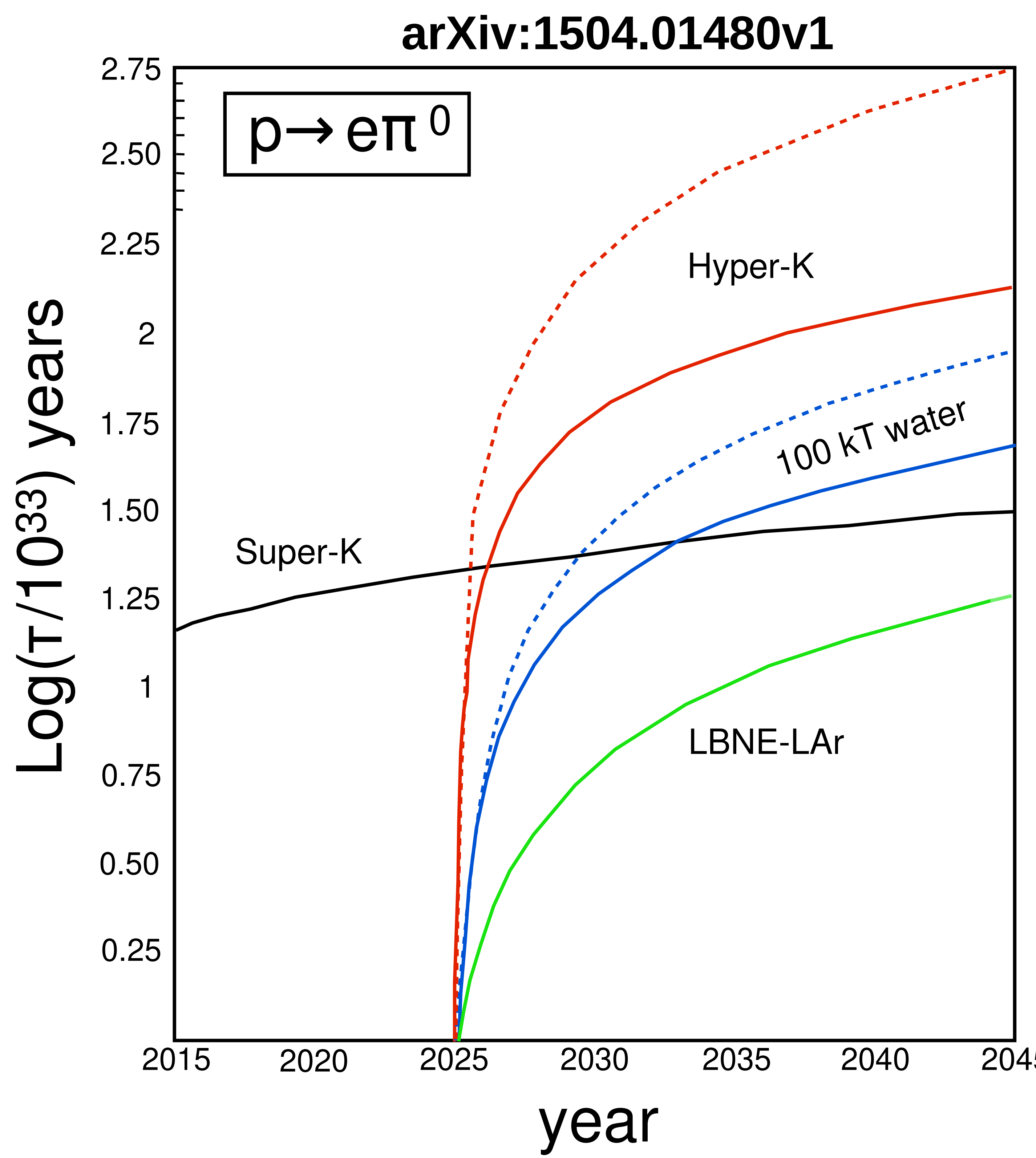
Current Super-K limit:

$\tau/B(p \rightarrow e^+ + \pi^0) > 1.6 \times 10^{34}$ years

K. Abe et al. (Super-Kamiokande Collaboration), Phys. Rev. D. 95, 012004 (2017)

Atmospheric neutrino backgrounds to proton decay

- The vast majority (90+%) of proton decays in water are not expected to involve final state neutrons
- As in DSNB searches, **atmospheric neutrino interactions** (some of which will involve final-state neutrons) generate the **dominant background**
- Neutron tagging with gadolinium expected to greatly reduce the background, but **neutron yields are uncertain**



The Experiment

Goals of ANNIE

- Primary physics goal: **measure neutrino-induced neutron yields** in water as a function of outgoing lepton kinematics

- **Demonstrate new technologies** that provide key functionality for the physics analysis

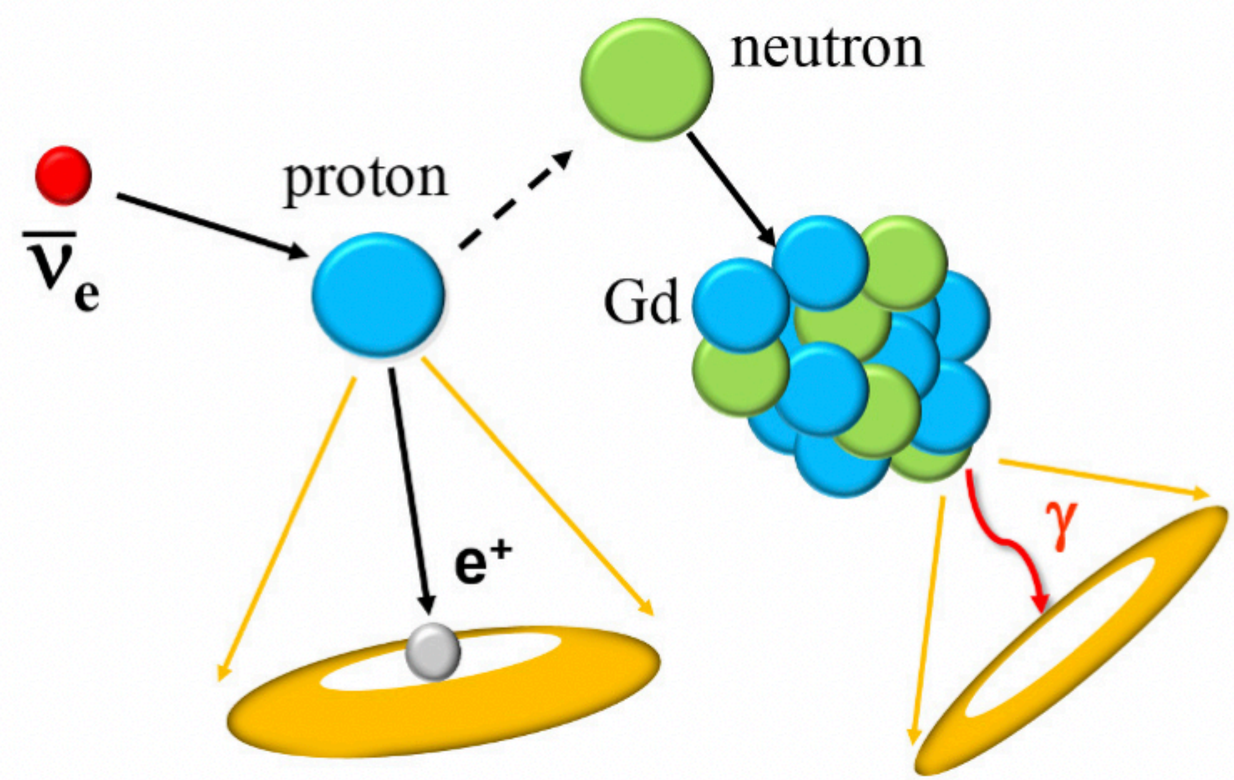
  - Gadolinium-loaded water for high-efficiency neutron tagging
  - Large Area Picosecond Photodetectors (LAPPDs) for precise event reconstruction

- Straightforward upgrades to the detector will allow the pursuit of a broader physics program

- ANNIE will provide helpful R&D for future large-scale experiments

Gadolinium loading for neutron detection

- Natural Gd thermal neutron capture cross section: **nearly 5×10^4 barns!**
- Produces a γ-ray cascade (total energy ~8 MeV)
- Added to scintillators as early as 1958
  - M. Hyman and J. J. Ryan, “Heavy elements in plastic scintillators”, *IRE Transactions on Nuclear Science* **5**, 87–90 (1958)
- Loading water Cherenkov detectors with Gd salts proposed in early 2000s
- 4.3 MeV average visible energy per capture in a water Cherenkov detector

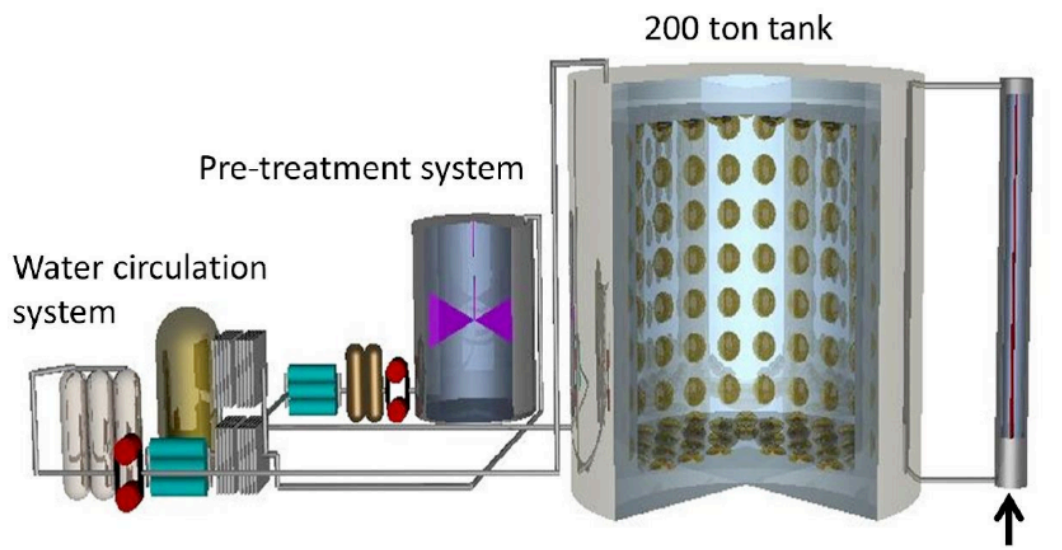


Inverse beta decay with neutron tagging

But can you really build a detector with water + Gd?

- **Water purity is key**: a big cross section doesn't help if you can't see the neutron captures!
- Material compatibility & recirculation
- > $10 million R&D effort to resolve these issues
- Two test experiments successfully operated (EGADS and WATCHBOY)
- **ANNIE will be the first experiment to apply this technique in a neutrino beam**, with SuperK-Gd coming soon after!

The EGADS detector



PMTs nice and clean after 2.5 years in EGADS!

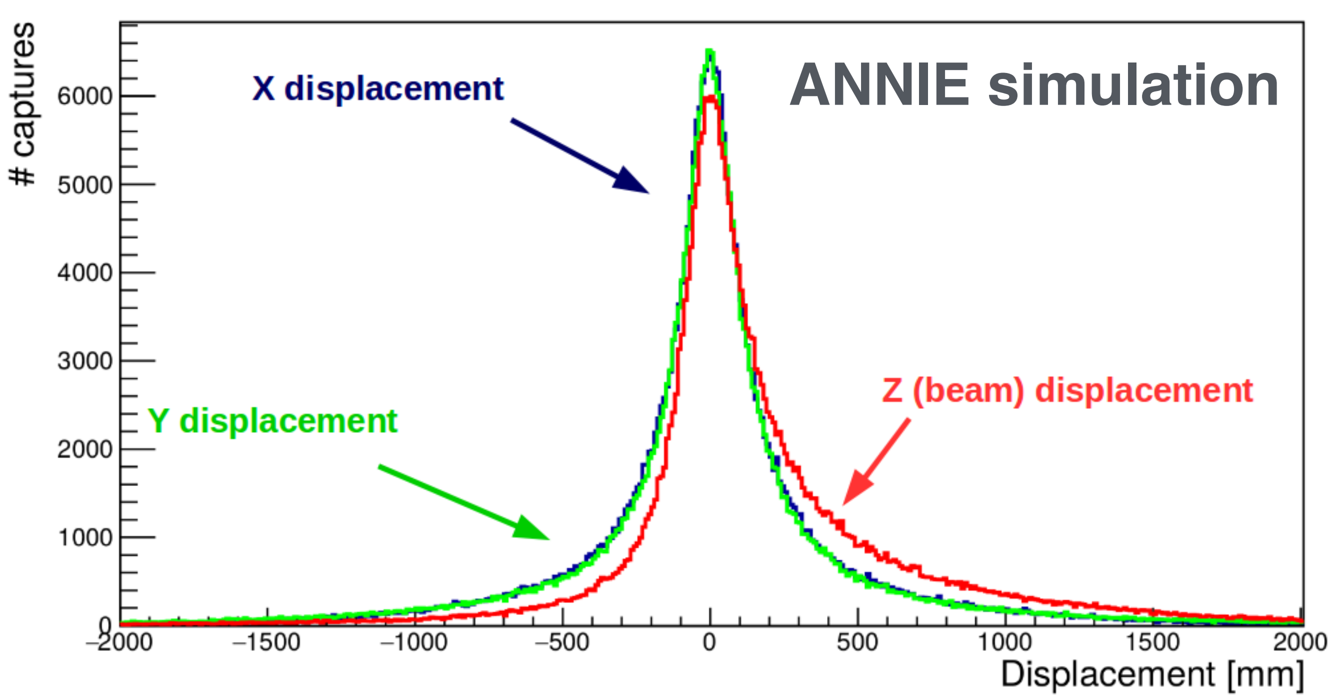
Fiducialization is needed to count neutrons

- High **neutron detection efficiency** and good neutron **containment** will be crucial for ANNIE's primary physics measurements

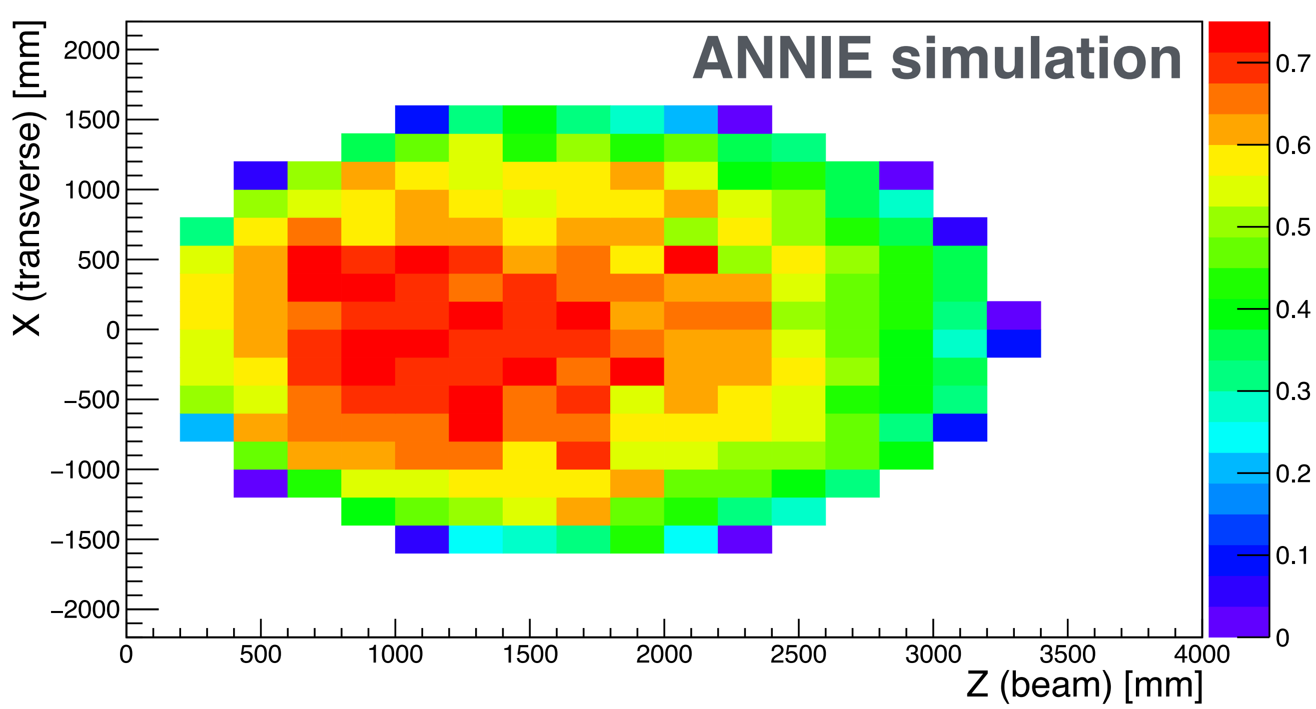
- At the tank edges, neutrons leak out, and light collection is poorer!

- A fiducial volume cut will allow ANNIE to avoid these problems.
  But how can we reconstruct a vertex position in water?

Displacement of neutron captures from neutrino vertex



Neutron detection efficiency (5 PE threshold)



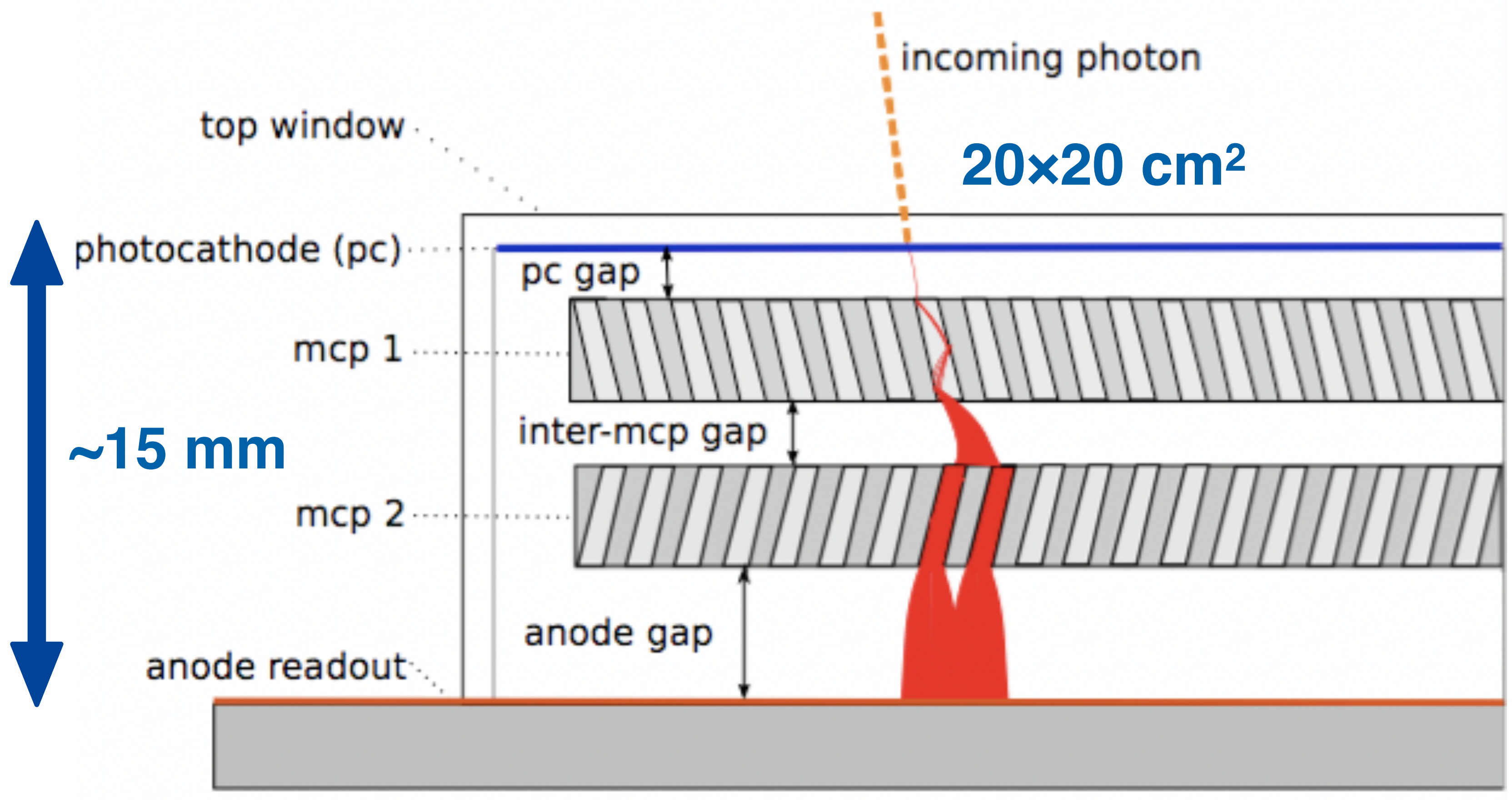
Large Area Picosecond Photodetectors (LAPPDs)

- 20 cm square micro channel plate (MCP)
- 60 ps time resolution
- < 1 cm spatial resolution
- > 20% quantum efficiency
- Low dark noise (< 100 Hz / channel)
- Commercialized by Incom, Inc.
- **ANNIE will pioneer event reconstruction using this new tool**

Co-spokesperson Matt Wetstein holding one of the ANNIE LAPPDs

Light detection with an LAPPD

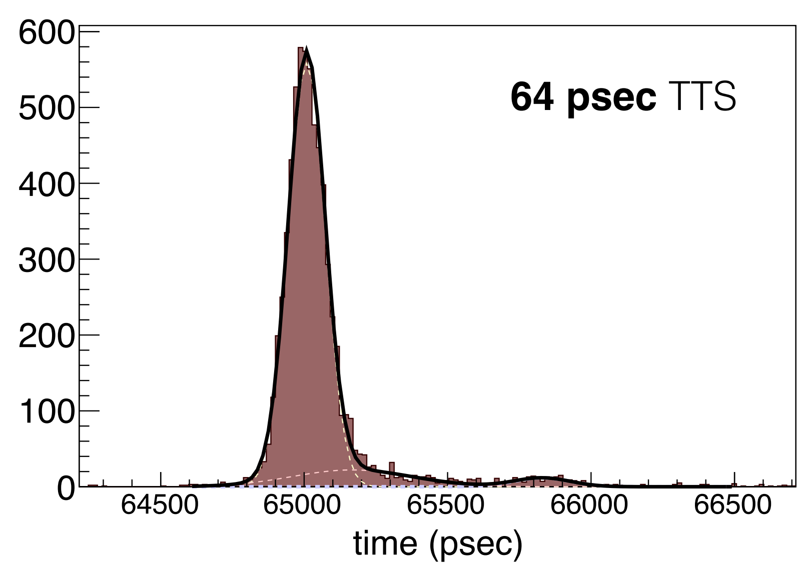
- Incoming photons produce electrons at the photocathode via the photoelectric effect
- Electrons enter microchannel plates (pore diameter ~10 μm)
- Collisions with the pore walls produce secondary electrons (Gain > 10^6)
- Signal collected on stripline anode
- Timing difference between strip ends used to recover longitudinal position

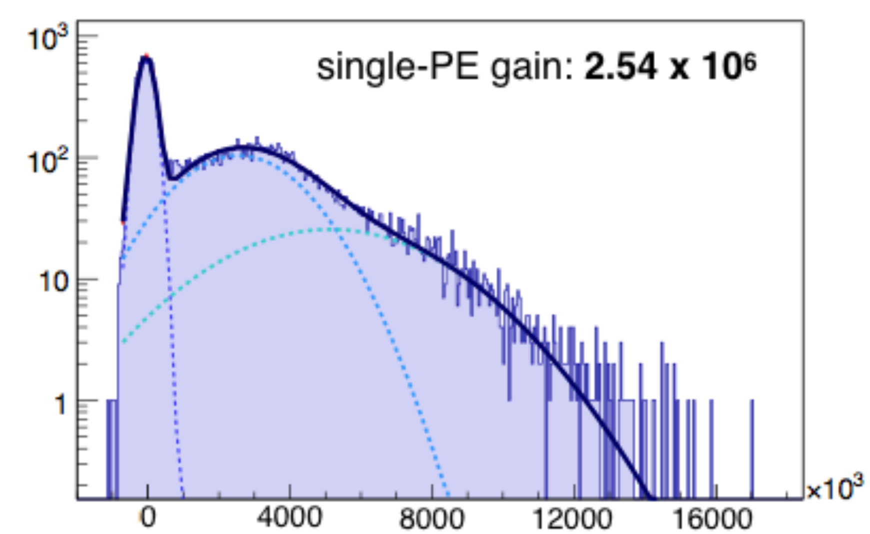


LAPPD status

- Incom Inc., with support of the DOE STTR program, built up the infrastructure for a first commercial product line of LAPPDs
- Incom is now able to produce early research-grade LAPPDs at a rate of 1-2 per month
- With Incom commissioning a second fabrication chamber yields/rates are expected to grow
- **ANNIE is the first purchaser**, with 2 LAPPDs in hand and 3 more expected to arrive over the next 5 months
- Incom is also starting to receive orders from other early adopters
- ANNIE testing results show that the LAPPD characteristics meet our specifications

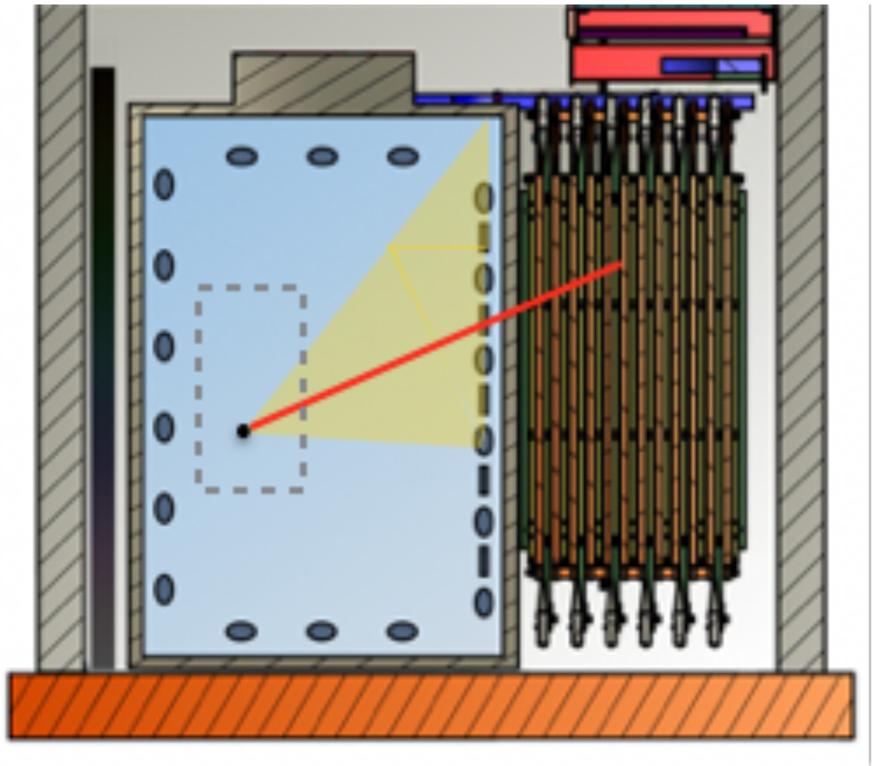


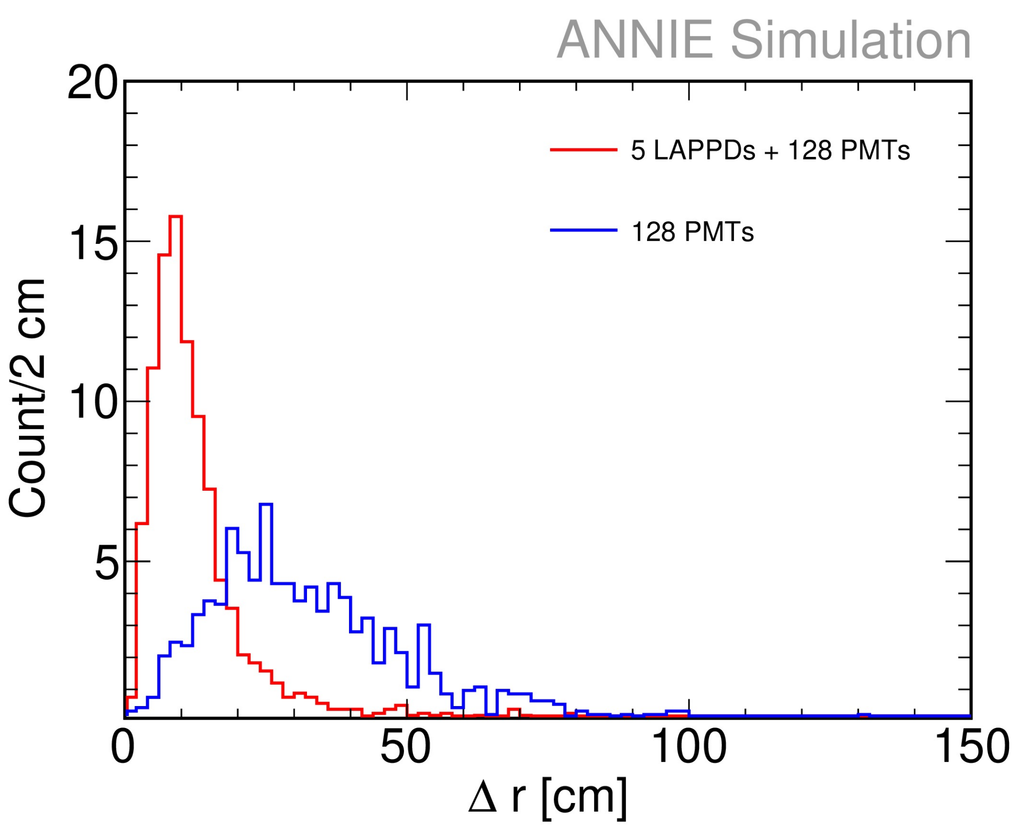



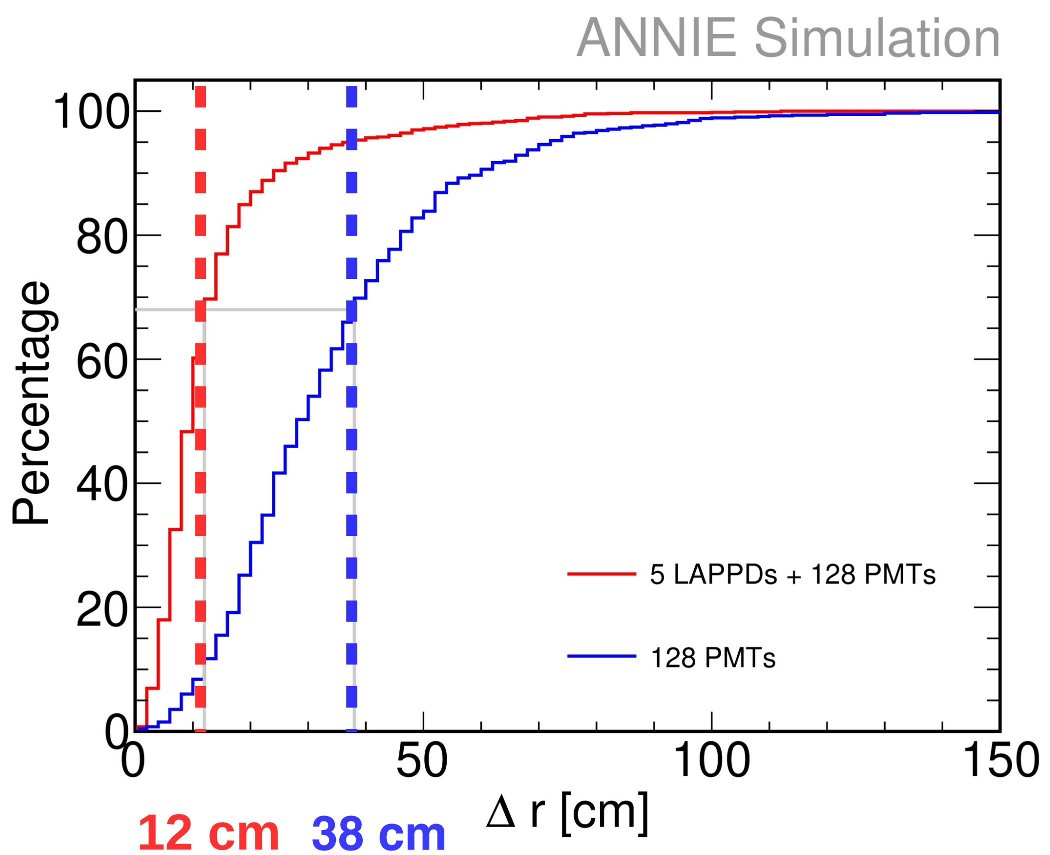


Need fiducialization in water? LAPPDs to the rescue!

- Adding just a few LAPPDs to the tank drastically improves the vertex resolution
- Significant impact on muon energy reconstruction and directionality
- Baseline design with 5 LAPPDs. Further improvements as more are added.



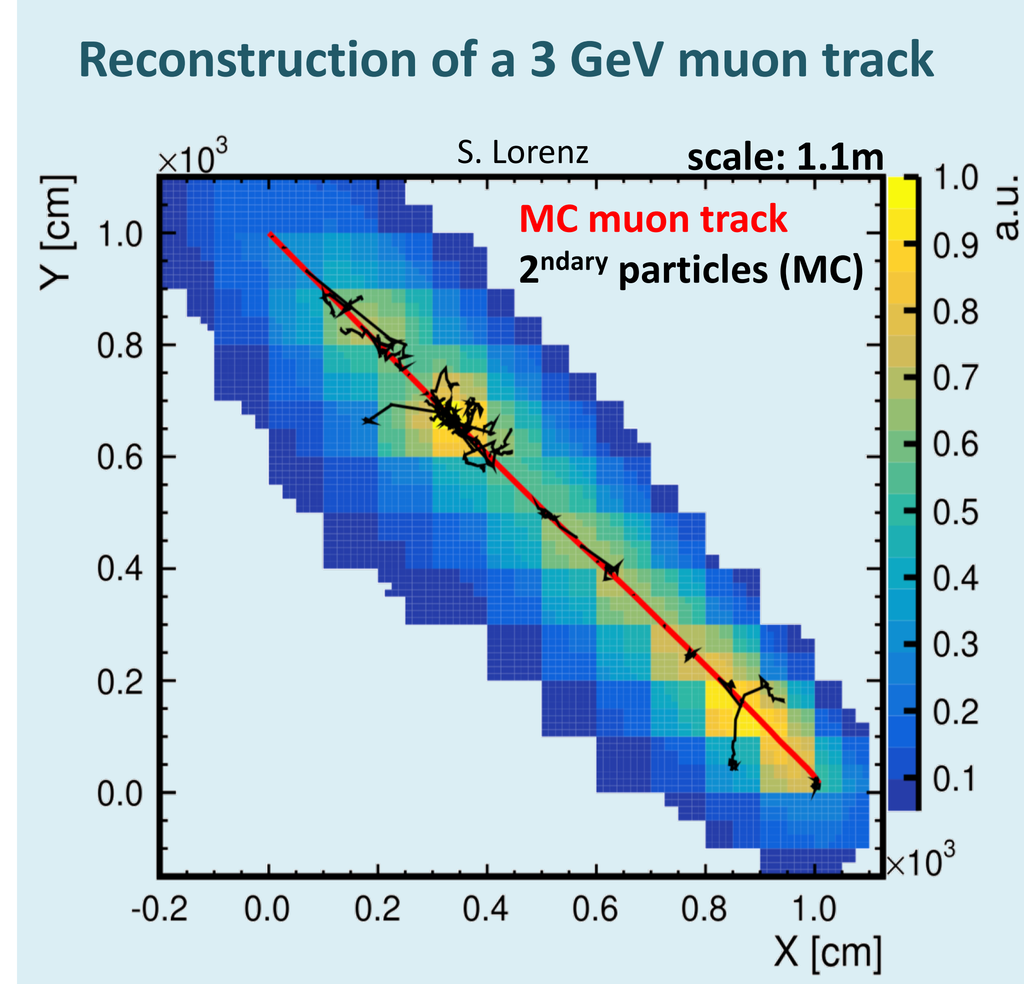




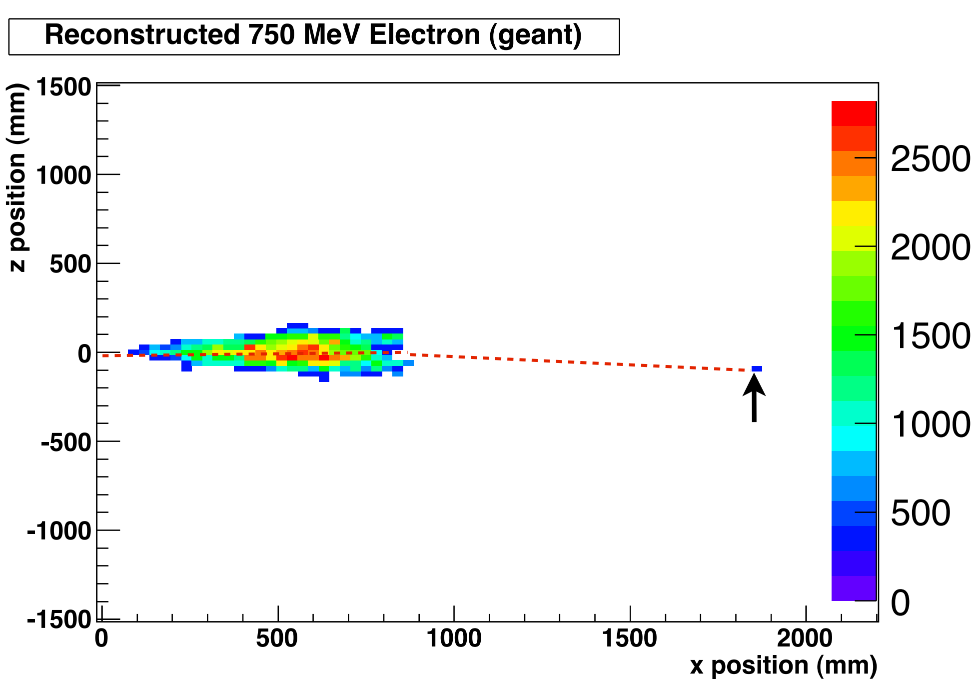
We plan to do even more with LAPPDs

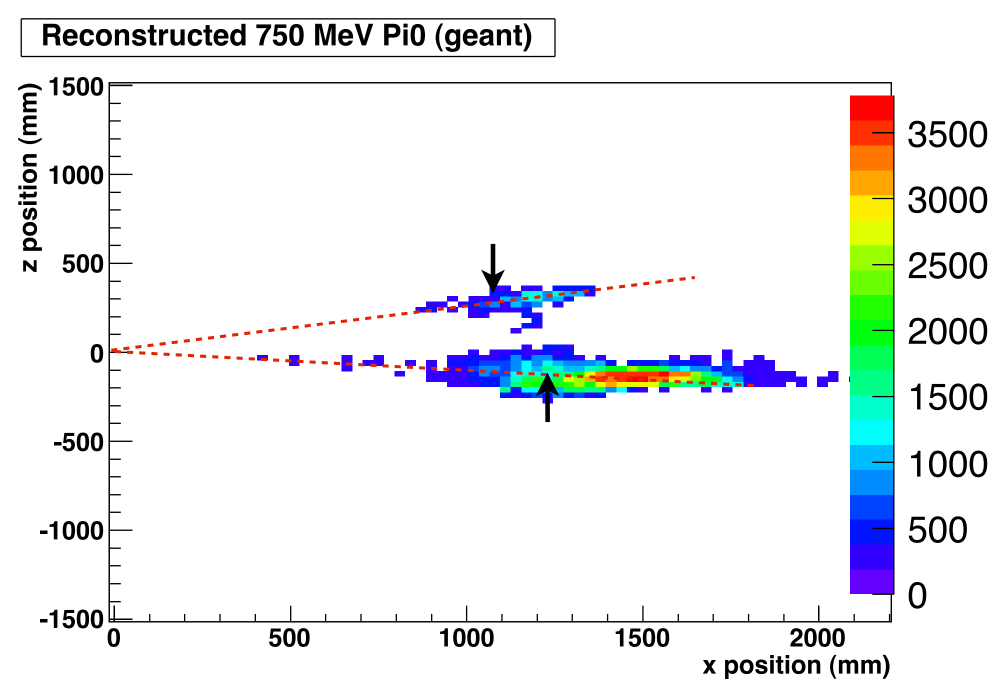
- With more LAPPD coverage and more sophisticated reconstruction techniques, we may be able to demonstrate more detailed topological reconstruction using time-reversal imaging techniques

- The ability to reconstruct multi-track events and wider angular acceptance would enable a broadening of the ANNIE neutrino cross-section program



Wonsak et al. https://arxiv.org/abs/1803.08802

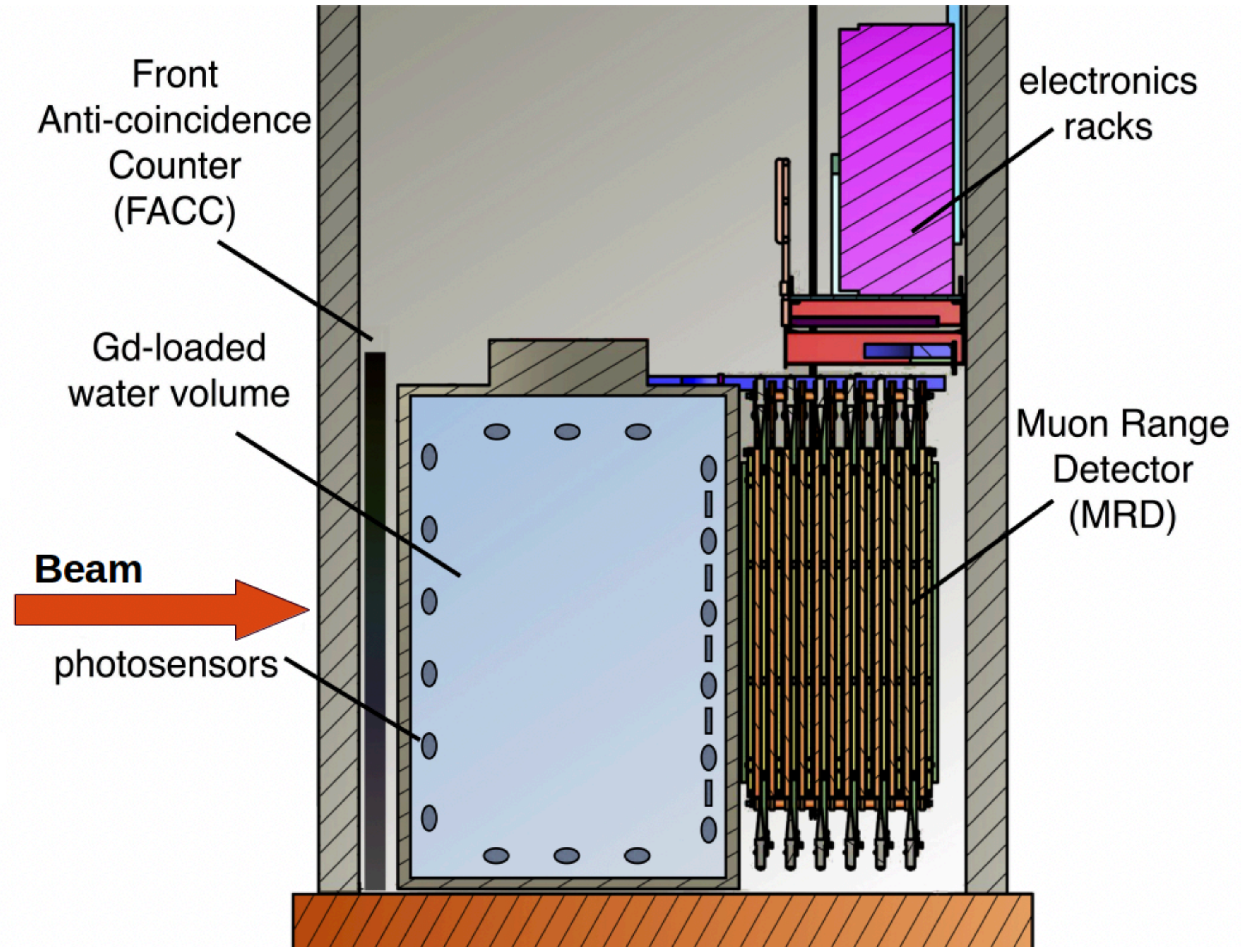




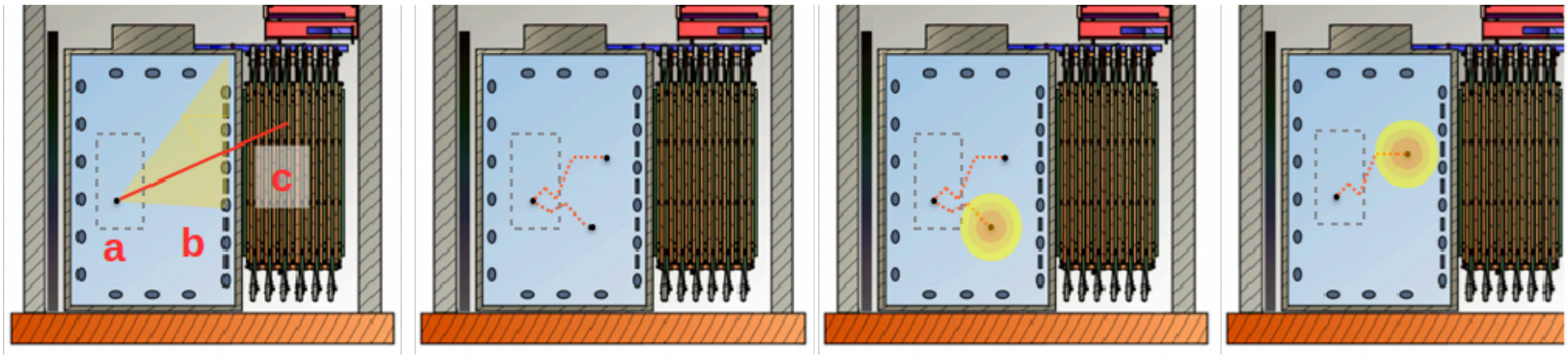
M. Wetstein, ANT11 (https://indico.fnal.gov/event/4887/)

The ANNIE detector

- 26 tons of **gadolinium-loaded water** (0.1% Gd by weight) in a steel tank
- **135 PMTs** and at least **5 LAPPDs** (~20% total photocoverage)
- **Front veto**: Scintillator paddles **tagging charged particles** originating from the rock upstream
- **Muon Range Detector (MRD)**: Steel-scintillator sandwich detector originally built for SciBooNE. Used for muon momentum reconstruction.
- **~10^4 CC interactions per ton per year** (2 × 10^{20} POT)



How will ANNIE work?



1 | **2** | **3** | **4**

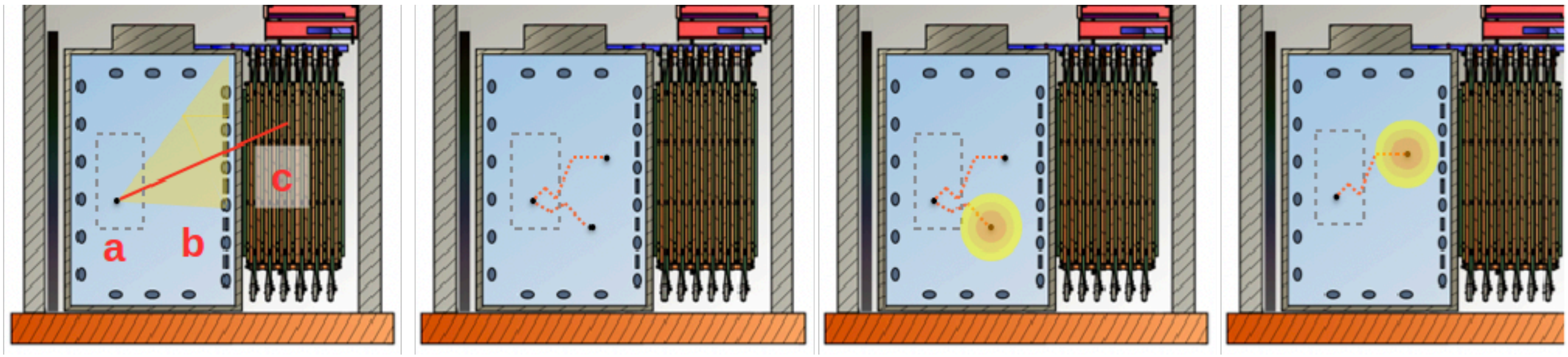
(first 30 ns) **(a few μs)** **(tens of μs)**

1. (a) Charged current interaction of ν_μ in the fiducial volume (dashed box)

   (b) Cherenkov cone imaged by photosensors. Used to reconstruct vertex position and muon momentum.

   (c) Muon ranges out in the MRD (also used for momentum reconstruction)

How will ANNIE work?



1 **(first 30 ns)**

2 **(a few μs)**

3 **4** **(tens of μs)**

2. Neutrons emitted at the vertex thermalize in the water volume

3–4. Neutron captures on Gd nuclei are detected by the PMTs & LAPPDs

ANNIE is a multi-phase experiment

- **Phase I**: Engineering run and background measurement **(completed)**
  - Spring ’16 to Summer ’17
  - Operated with a partially instrumented version of the full detector
  - Performed background measurements
  - LAPPD testing and characterization outside of the detector

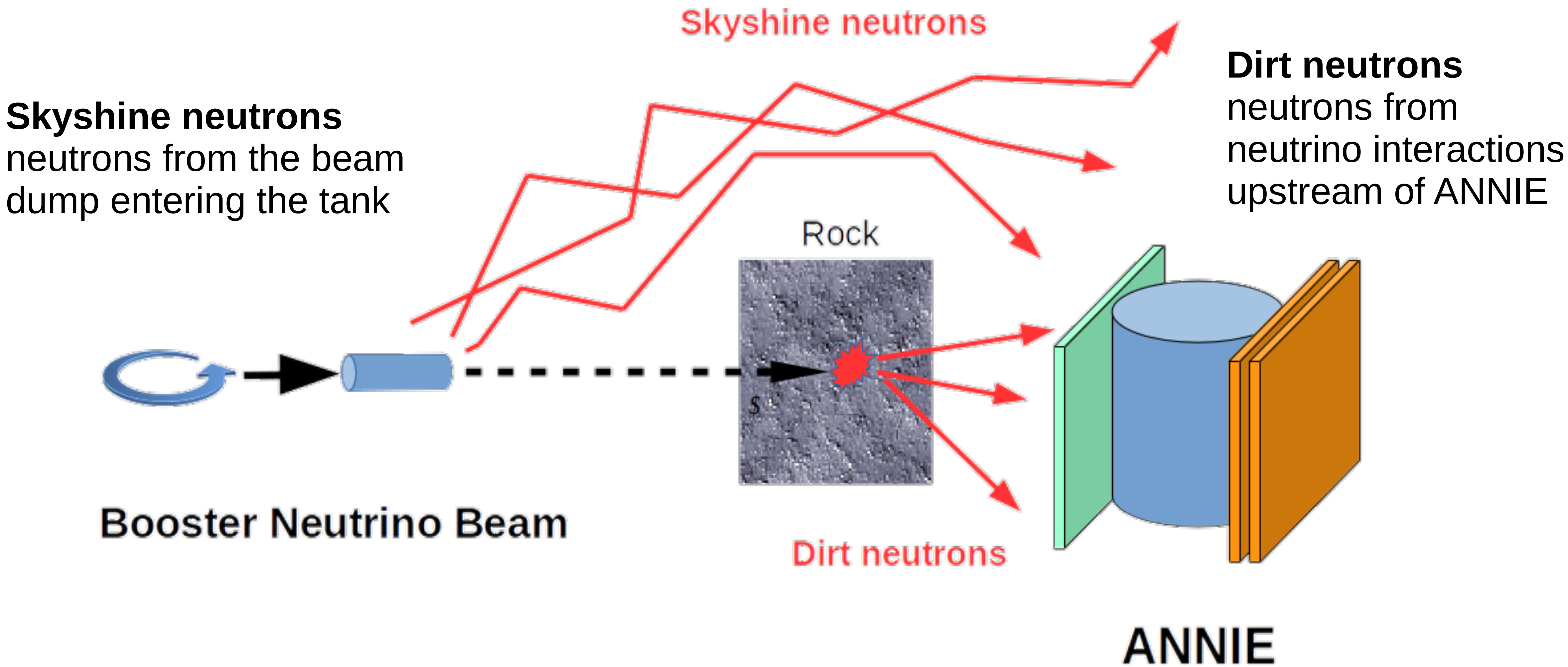
- **Phase II**: Physics run **(funded, under construction)**
  - First data expected this spring
  - Full detector, including LAPPDs and Gd-loaded water
  - Measure neutron multiplicity, cross sections, etc.

- Possible **Phase III**:
  - Add water-based liquid scintillator to the tank

ANNIE Phase I

ANNIE Phase I: neutron background measurement

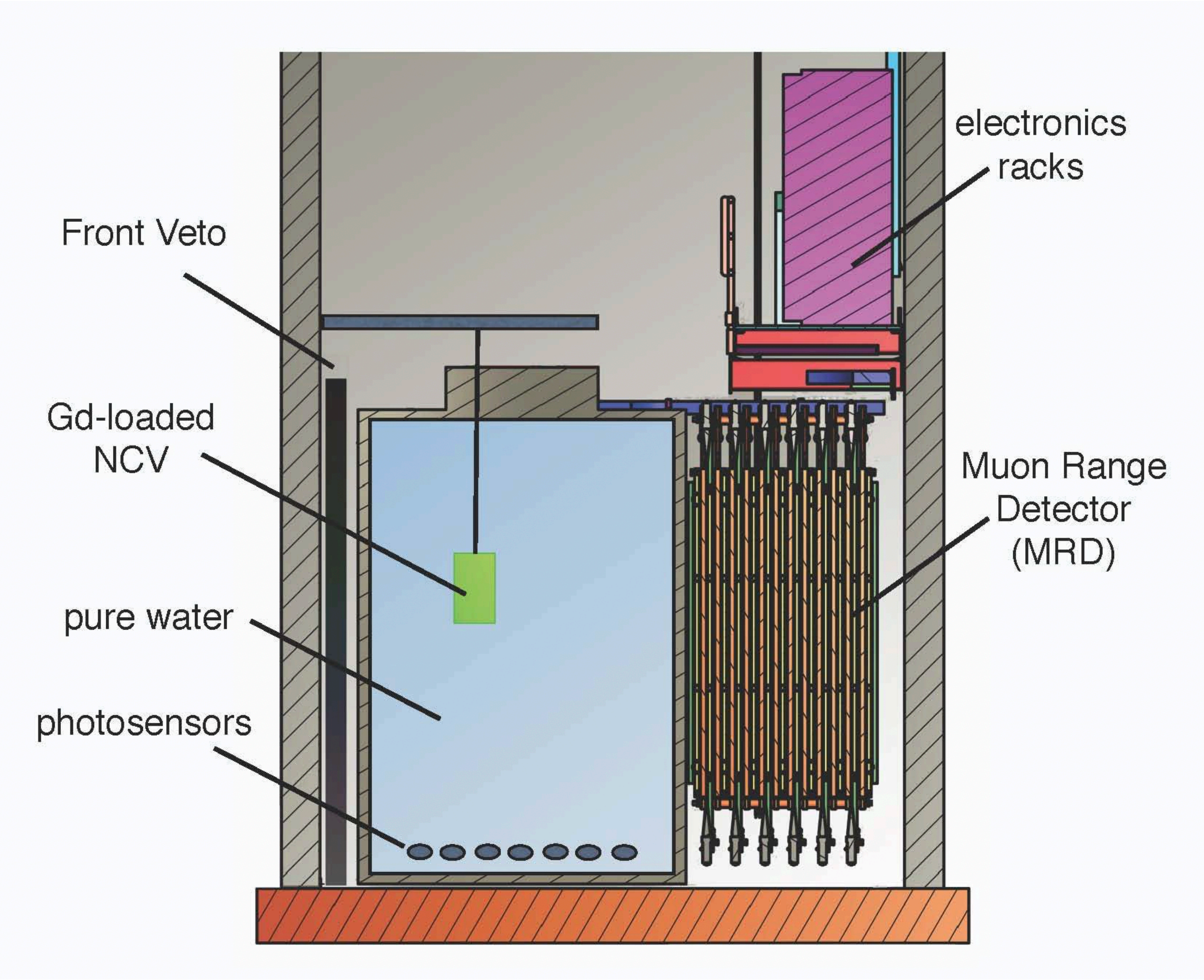
"measure and understand beam-induced neutron backgrounds to the physics measurement to be conducted in Phase II"

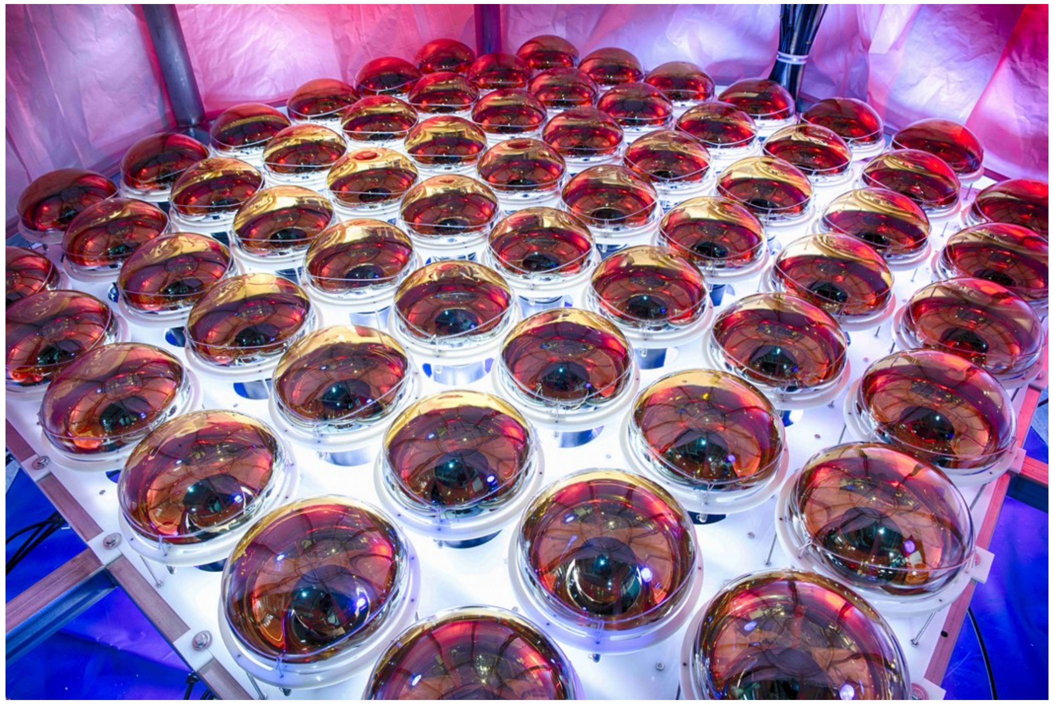


- Installation at SciBooNE hall: March – May 2016
- Data taking: June 2016 – September 2017
- **Different detector configuration**

Phase I detector configuration

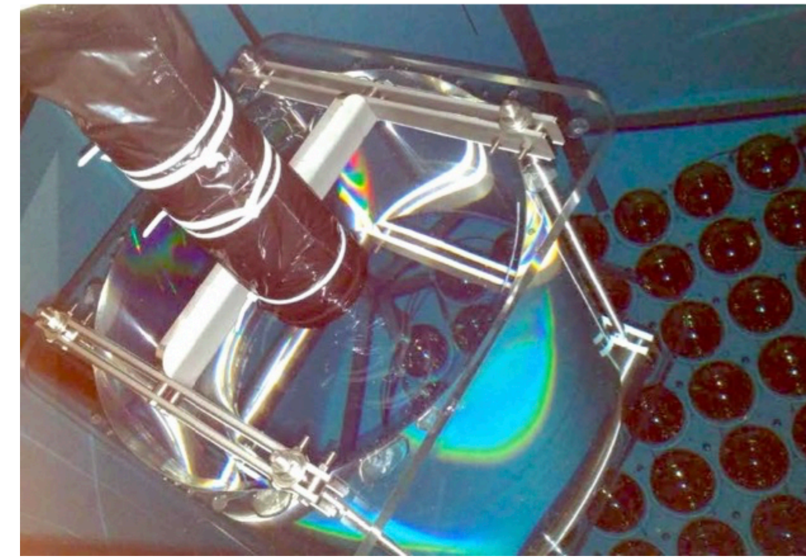
- **60 PMTs** installed at the bottom of the tank, white liner on inside of tank
- Two layers of MRD active (pre-refurbishment)
- **Neutron Capture Volume (NCV)**
  - Movable neutron-sensitive subvolume of the detector
  - Used to characterize position-dependent background neutron capture rates
- Tank PMTs used to **detect and veto cosmic-ray and beam-induced muons**

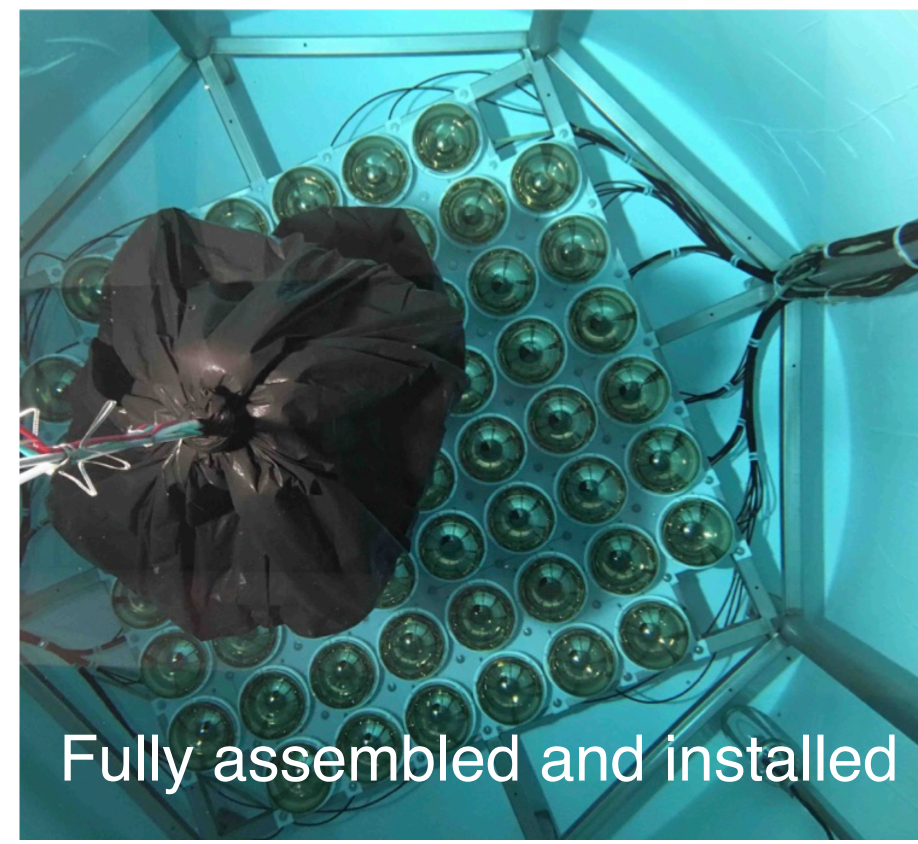




Neutron Capture Volume (NCV)

- Movable 50 cm × 50 cm acrylic vessel
- Enables position-dependent neutron capture rate measurement
- Filled with 0.25% Gd-loaded liquid scintillator (EJ-335)
- Optically coupled to two PMTs
- Wrapped in white plastic and an outer black bag **(optically isolated from the rest of the tank)**

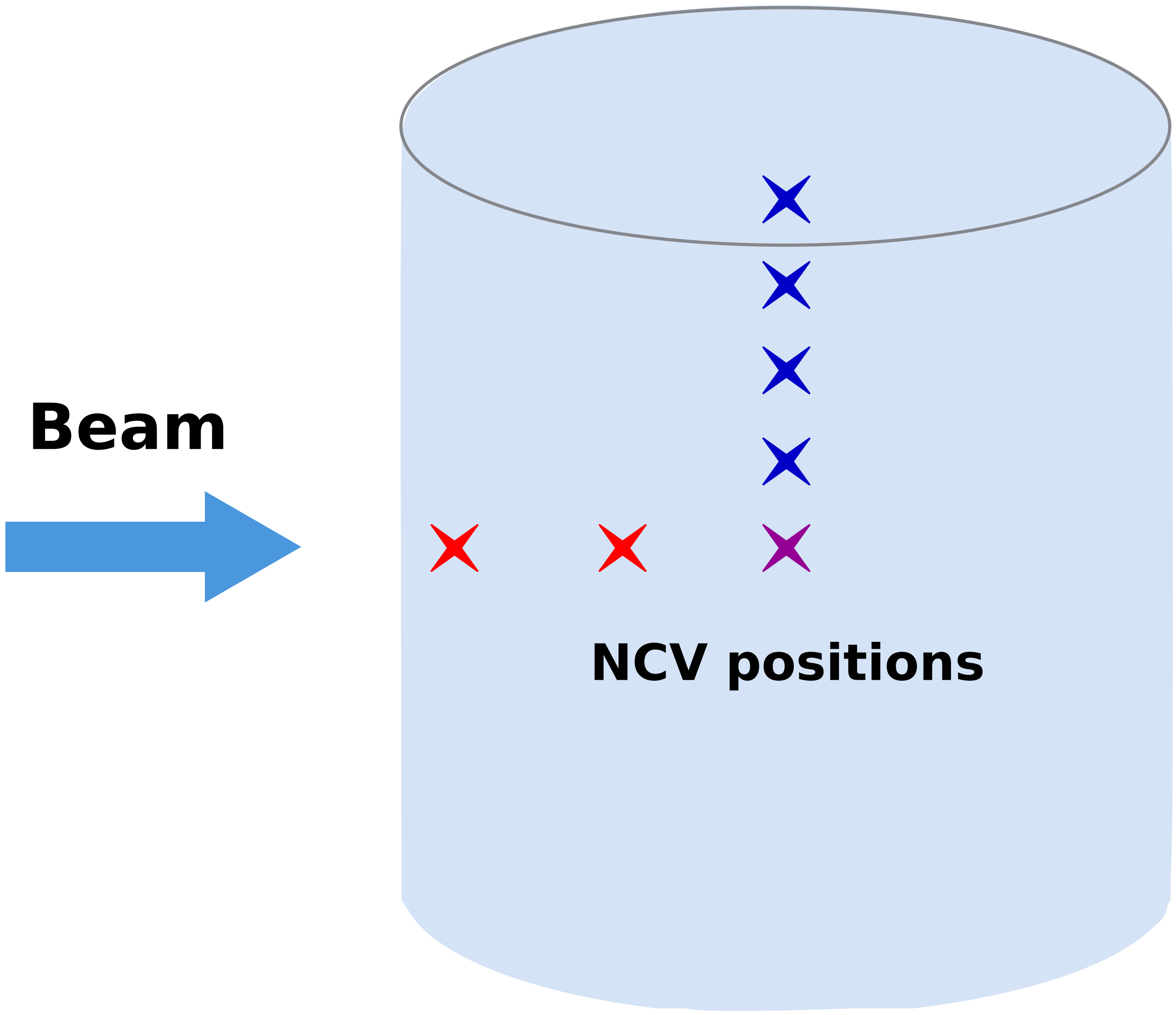




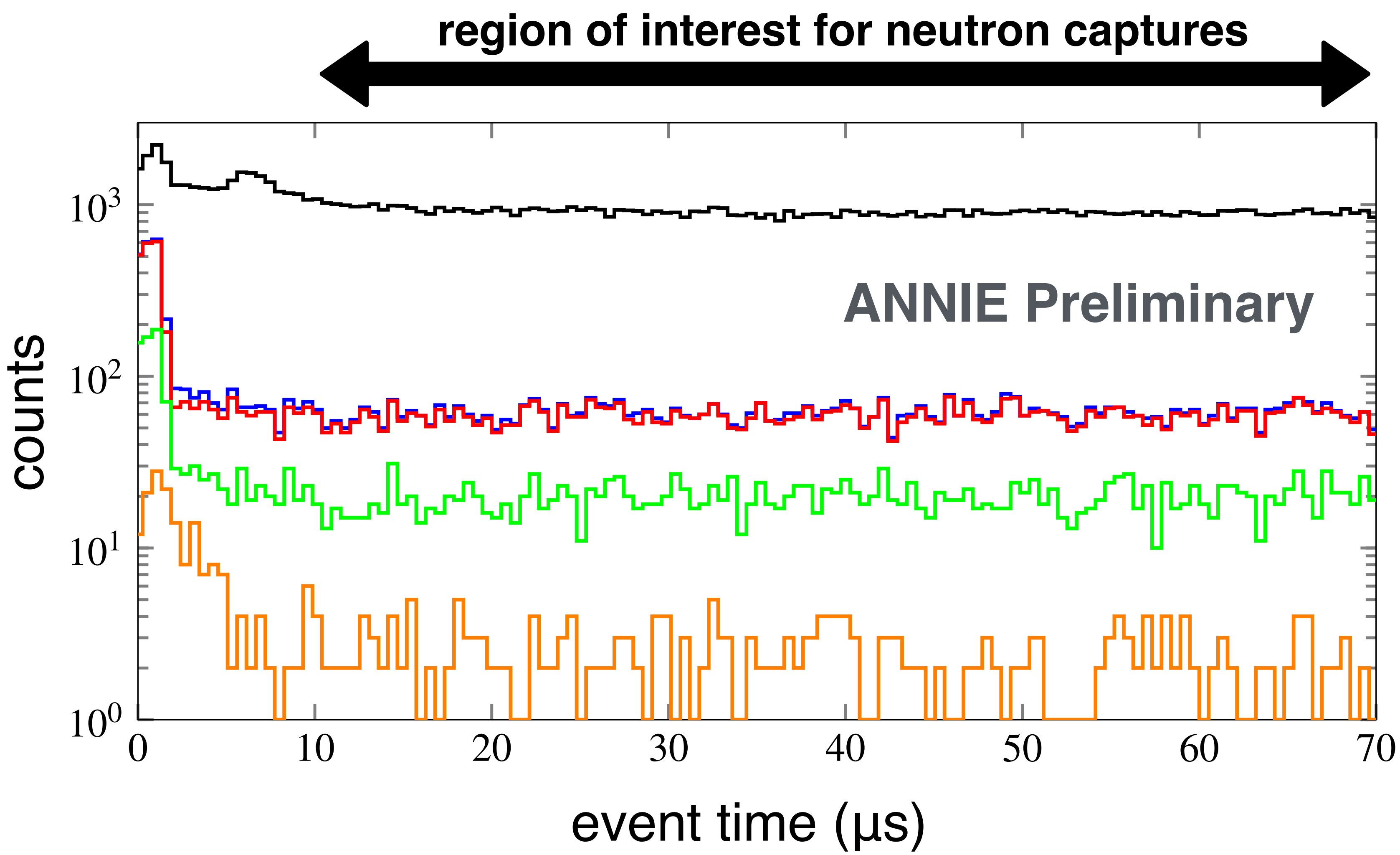
Fully assembled and installed

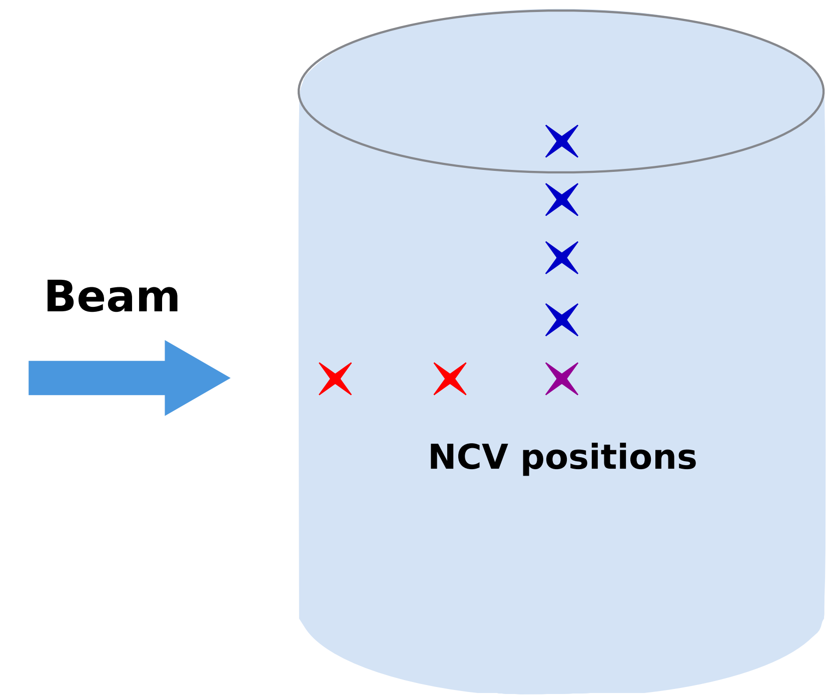
NCV position scan

- The NCV was moved vertically and horizontally to measure neutron backgrounds at 7 different locations within the tank
- Skyshine contribution was expected to be largest at the top of the tank
- If background rates are significant near the outside of the tank, how much water buffer do we need?



Neutron candidate event selection





Data shown are from the center of the tank (marked in purple)

(black) Raw event counts

(blue) Coincidence of both NCV PMTs

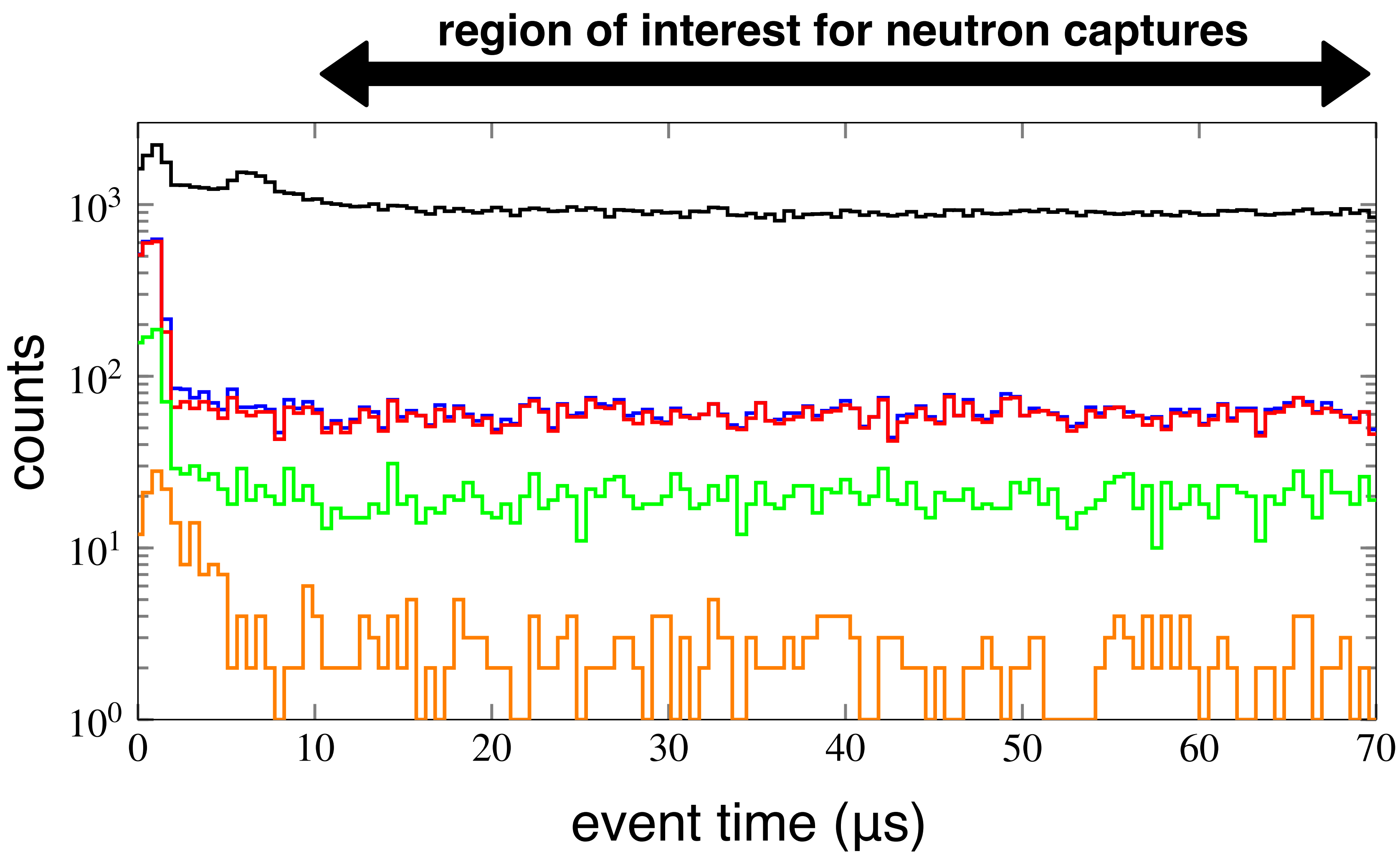
(red) At least 10 μs since last event (afterpulsing veto)

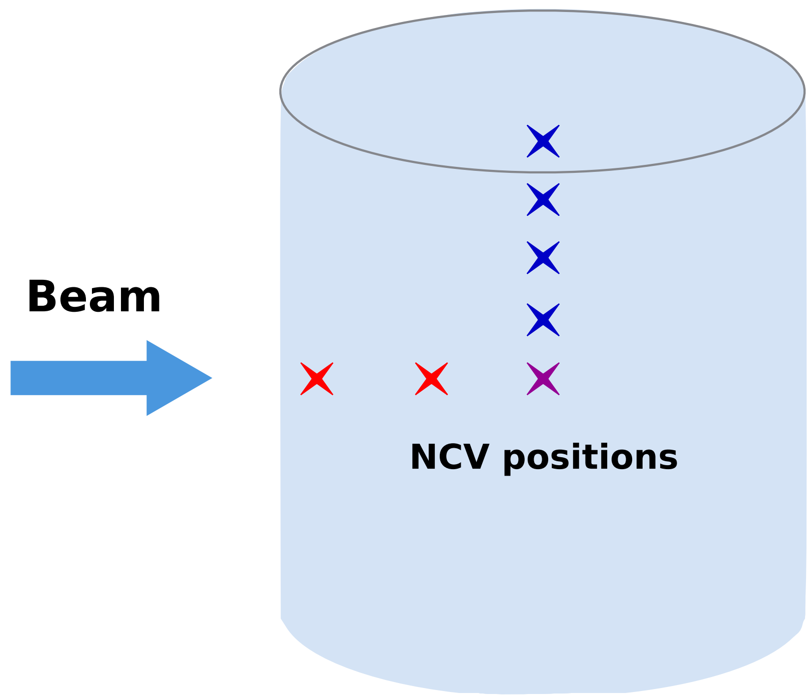
Remove noise hits

(green) Total NCV PMT charge < 150 pC

(orange) < 8 coincident water tank PMTs

Neutron candidate event selection





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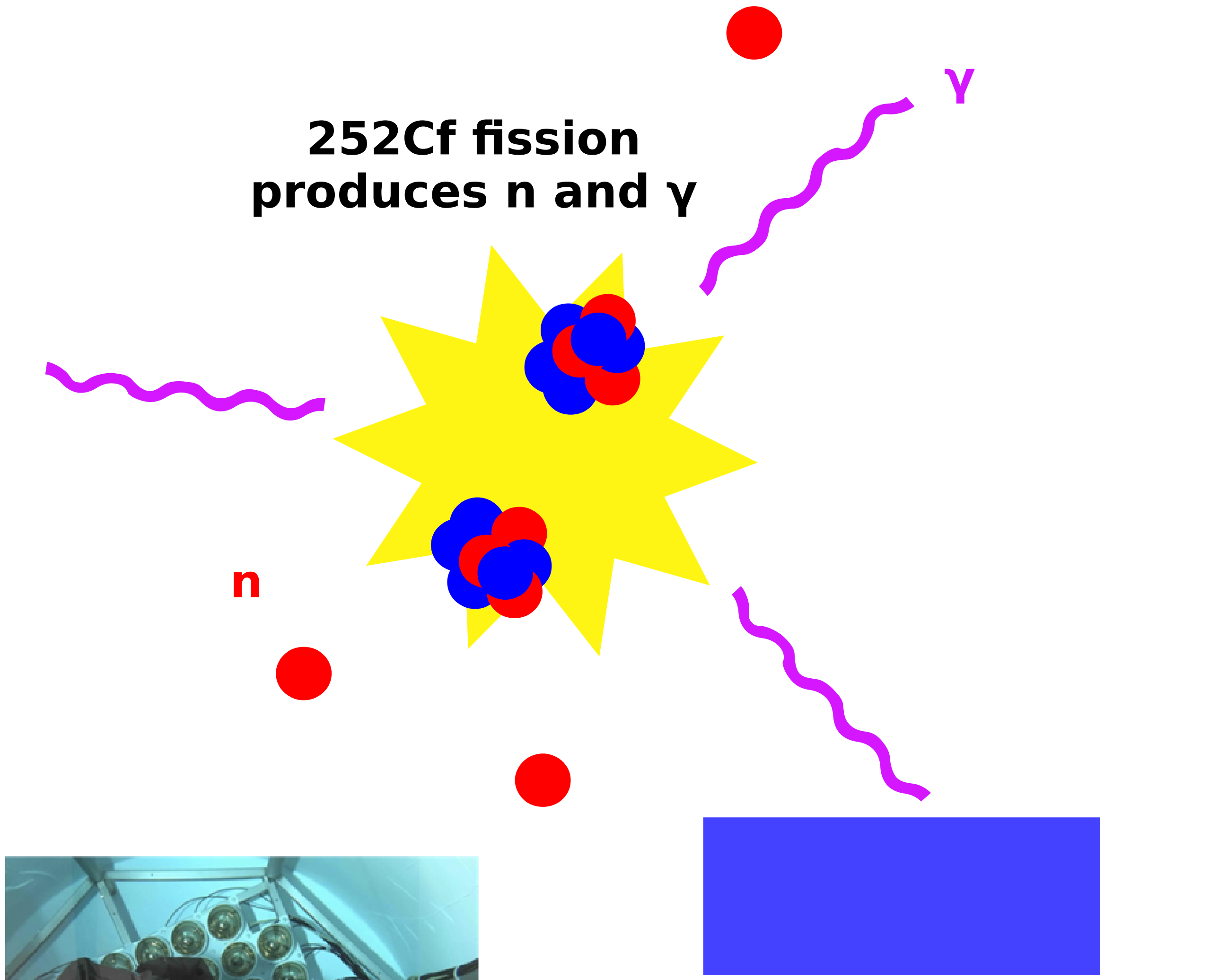
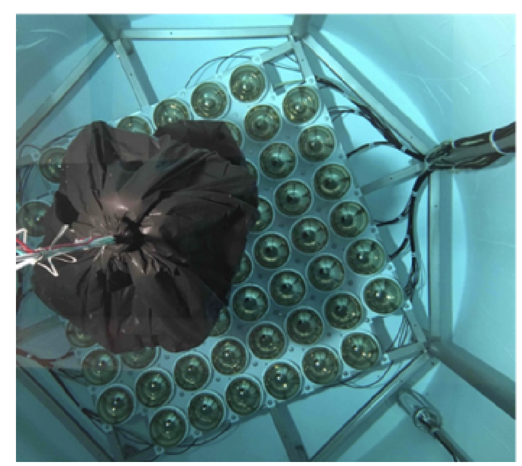
Remove cosmics and beam events

NCV efficiency calibration

- A californium-252 fission neutron source was used to calibrate the NCV
- LYSO crystal + small PMT used to trigger ANNIE on fission γ-rays
- Subsequent neutron captures detected by NCV at top of the tank
- Compared with Monte Carlo simulation to determine efficiency

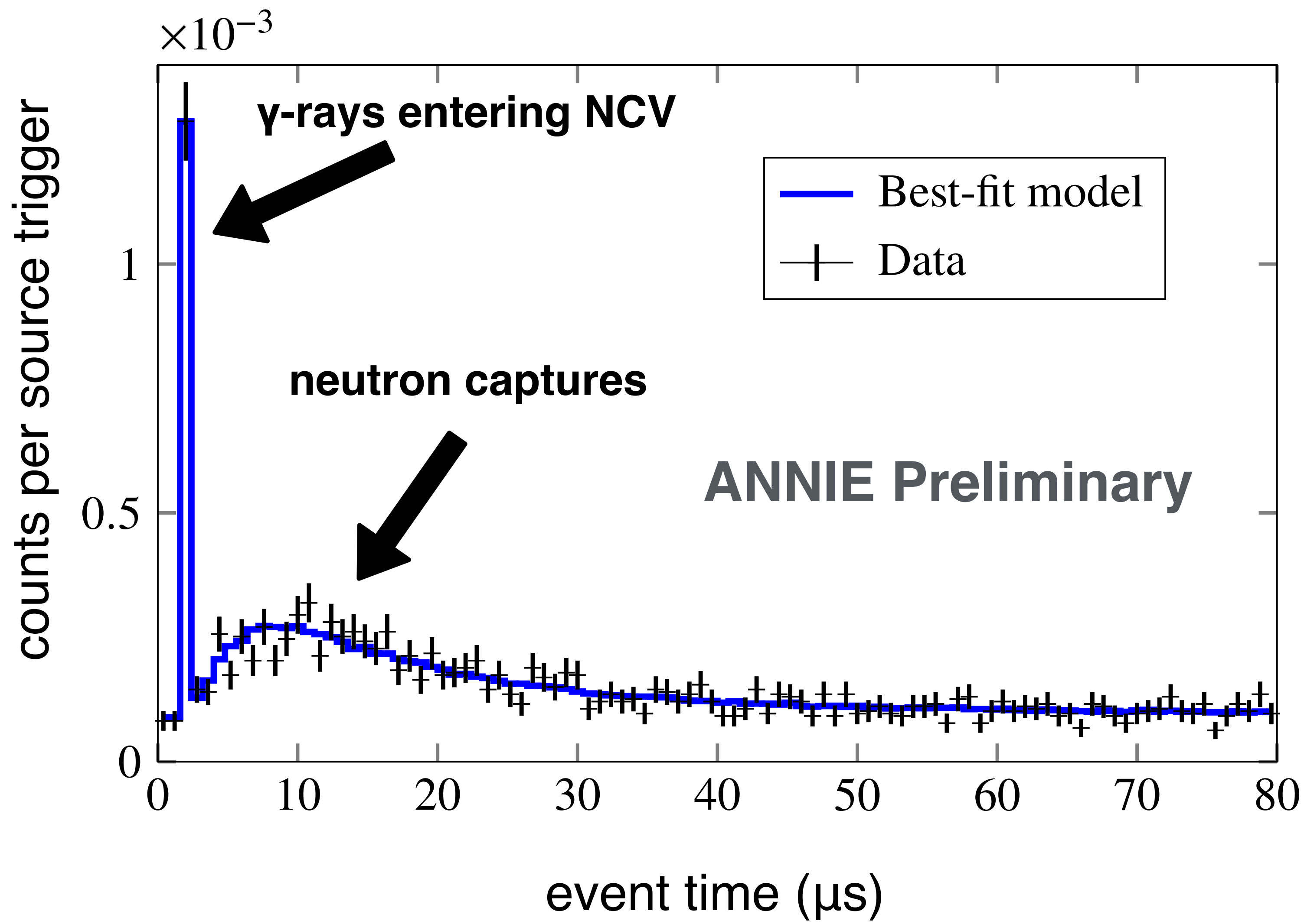




NCV detects fission neutrons

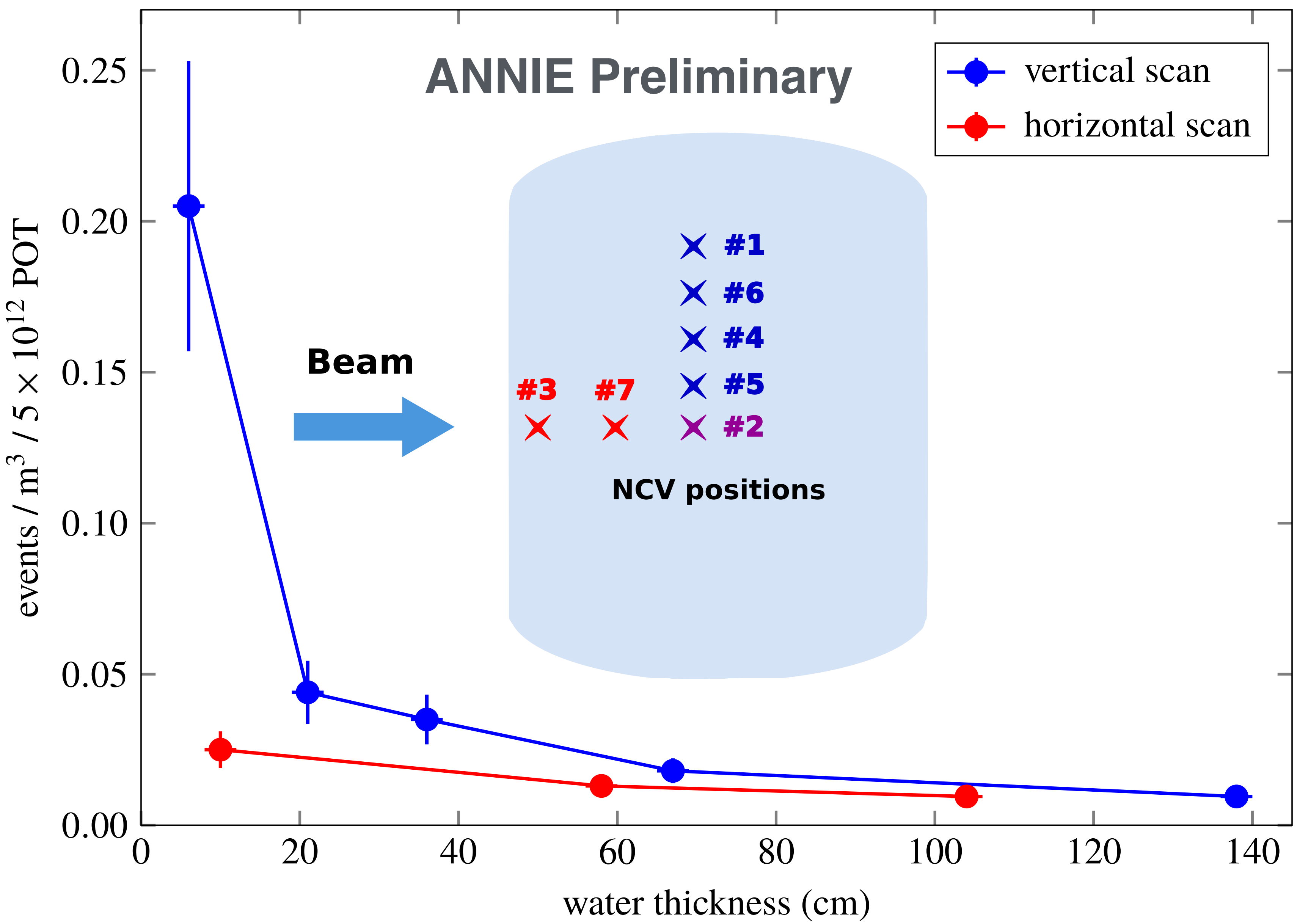
NCV efficiency calibration

- Source calibration runs were simulated
  - FREYA (Fission Reaction Event Yield Algorithm) generator
  - RAT-PAC detector simulation
- Simulation results fit to data using a scaling factor plus a flat background
- Systematics estimated by comparing to independent cosmic-ray calibration technique
- **NCV Efficiency:**
  10.5 ± 0.5 (stat) ± 2.3 (syst)%



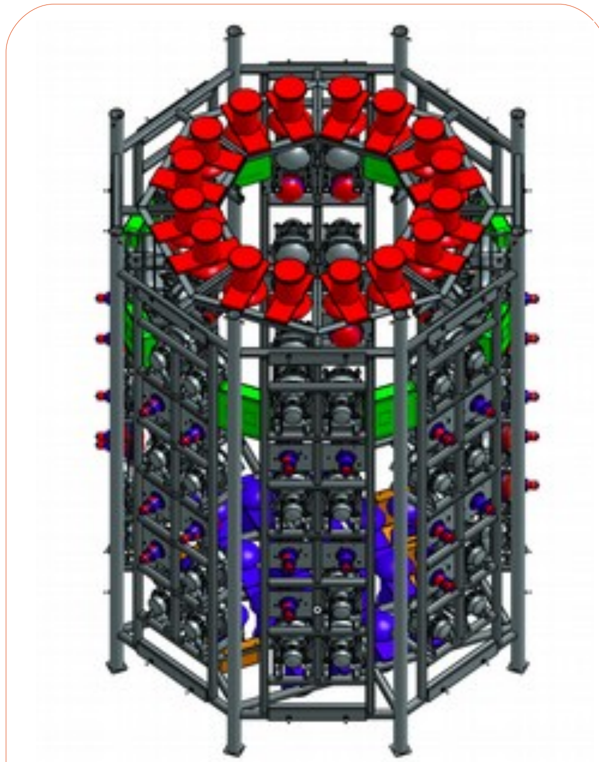
Background event rates

- High rate near the top of the tank (consistent with skyshine) falls sharply with increasing water overburden
- Average of **0.02 neutrons / spill / m³** in the Phase II fiducial volume
- **Backgrounds are manageable. Phase II may proceed!**
- Publication to be submitted soon



ANNIE Phase II Status

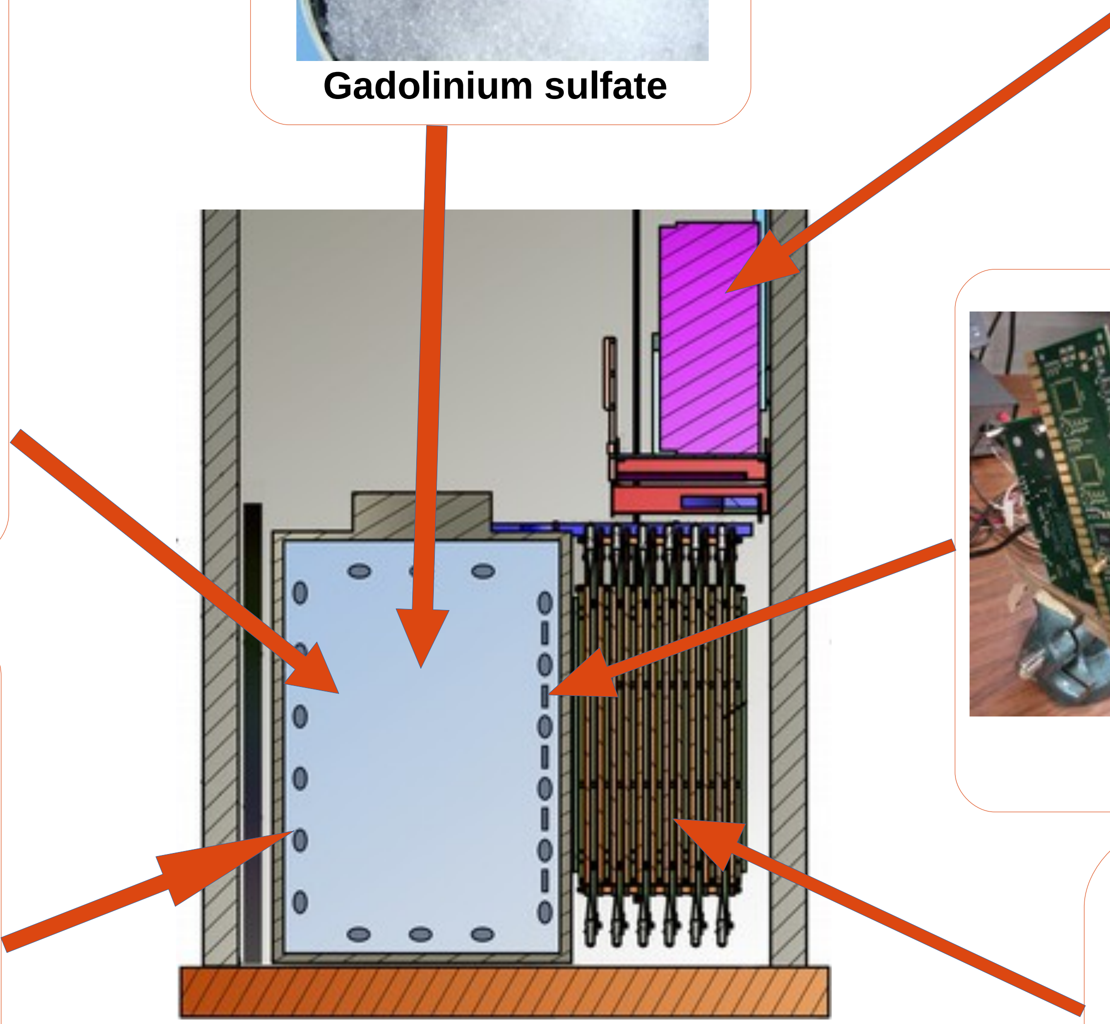
Phase II is fully funded and under construction at Fermilab



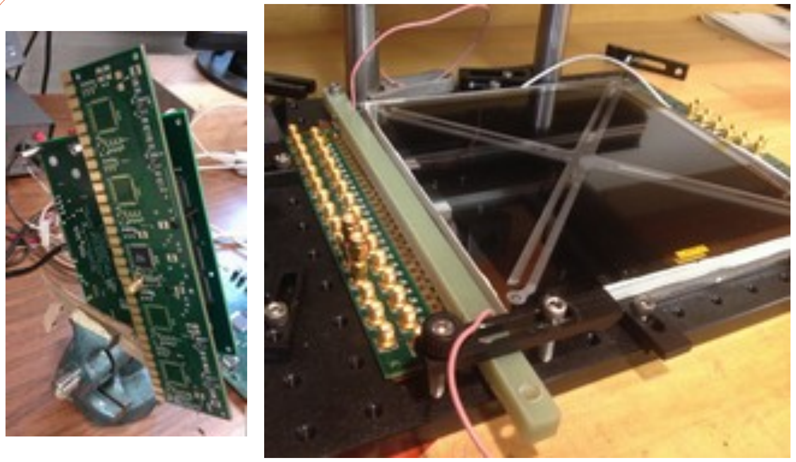
New inner structure

Gadolinium sulfate

New fast electronics

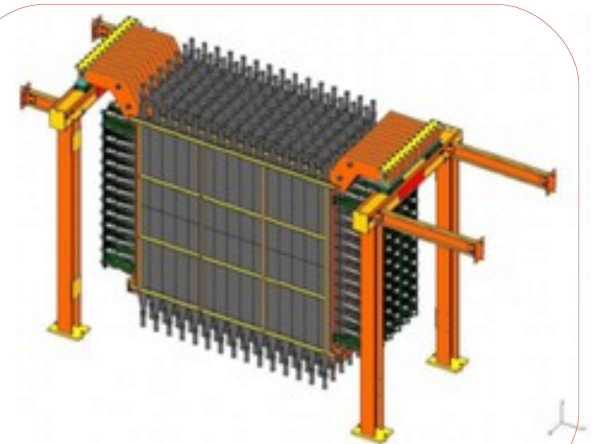


The Phase II detector



LAPPDs and fast readouts

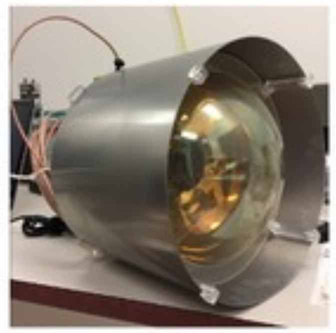
Additional PMTs



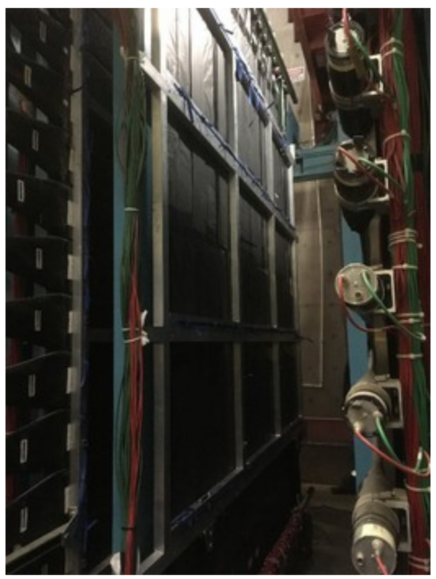
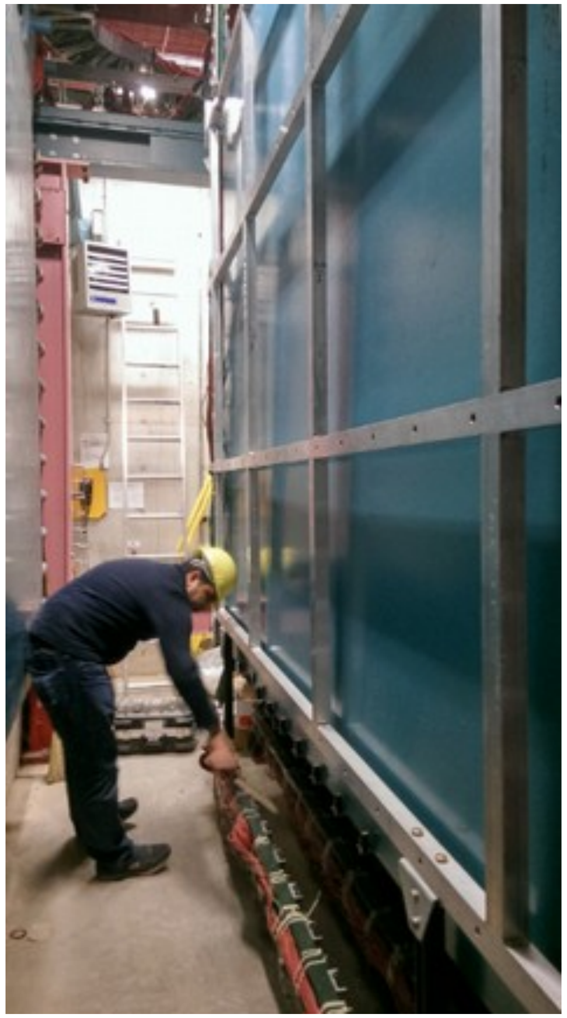
Fully refurbished MRD

Phase II is fully funded and under construction at Fermilab





Most **PMTs onsite** and **ready to be tested/installed**!


Muon Range Detector now **fully refurbished!**

HV and electronics **racks ready** to be populated!

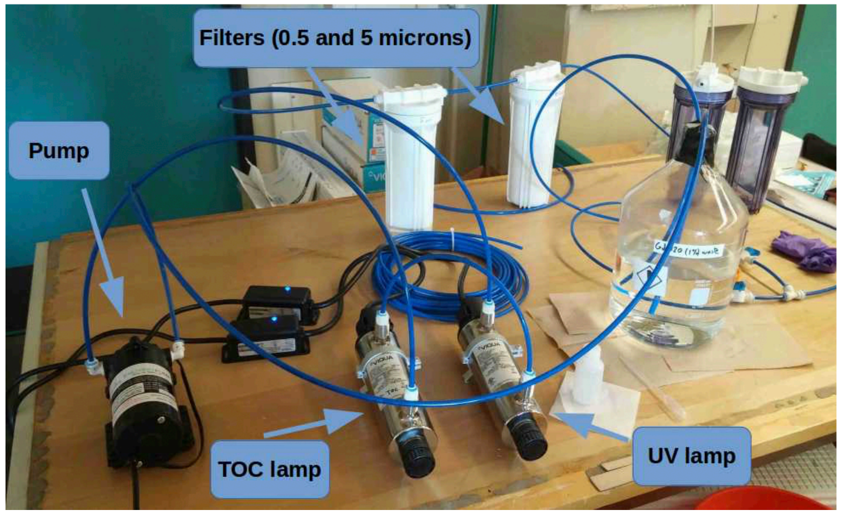
Phase II is fully funded and under construction at Fermilab

Stainless steel **inner structure** being **welded and mounted!**

Gd recirculation

- Tabletop Gd water filtration system undergoing testing at UC Davis
- **R&D partially in common with EGADS** (through Mark Vagins, an ANNIE collaborator)
- ANNIE needs a cheaper yet efficient filtration system
- Work in progress to scale up test system for use with ANNIE

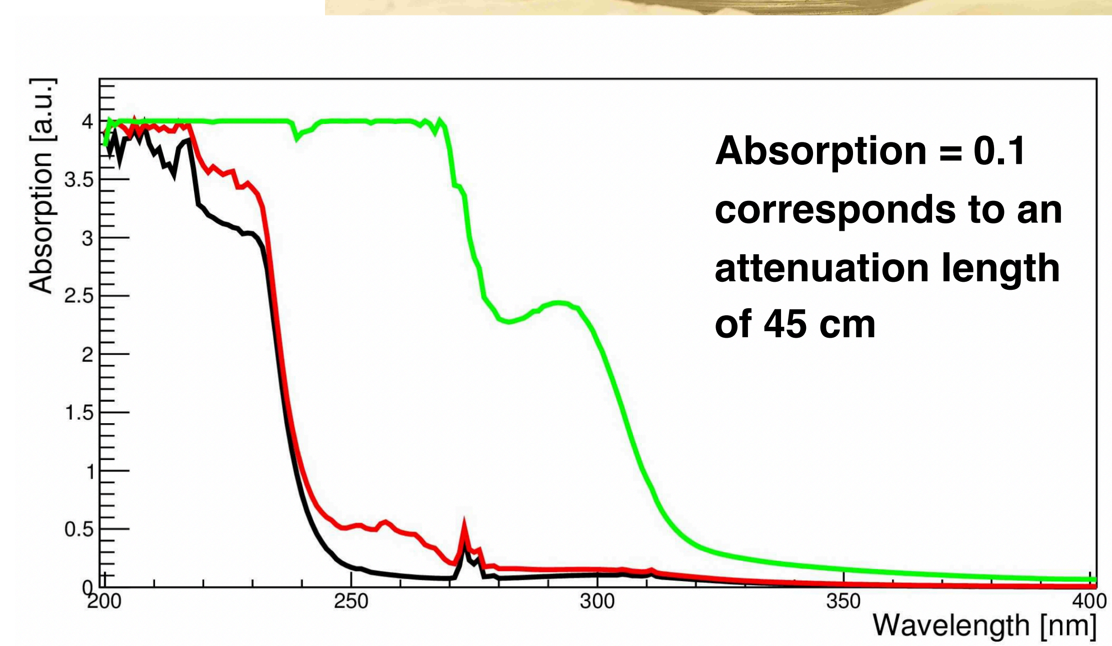
Dissolving Gd sulfate at UC Davis



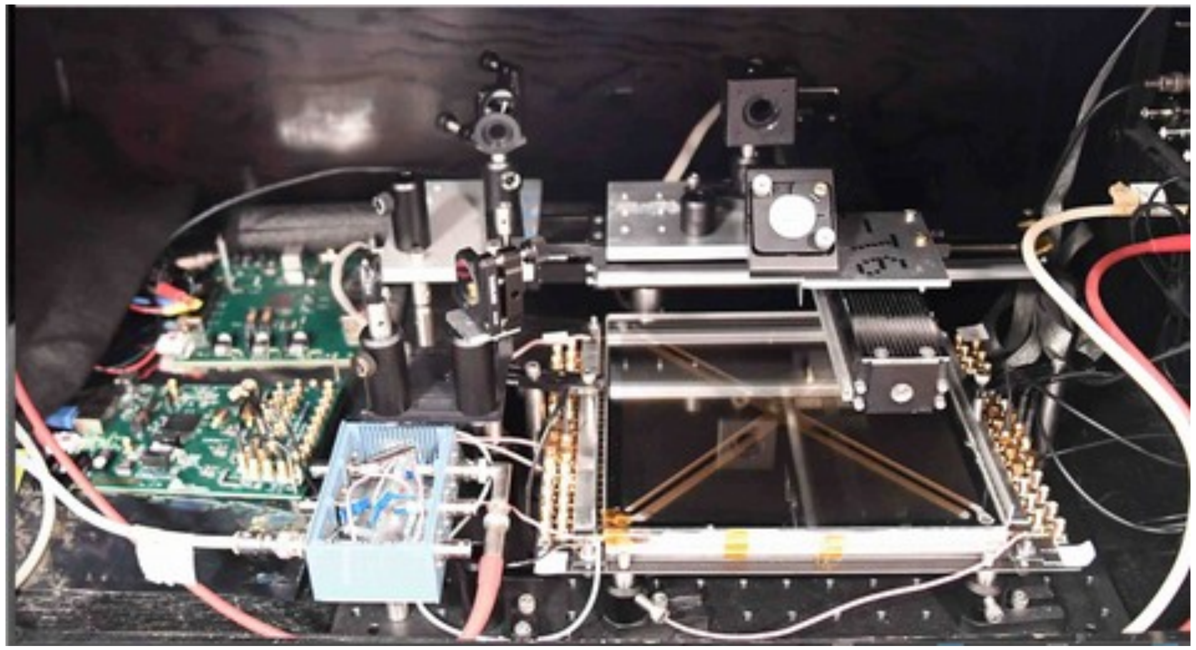
Gd compatibility testing

- Gd sulfate is not corrosive, but it still reacts with some materials
- Meticulous compatibility studies are being performed for every material that will enter the tank
- To maintain the needed water transparency, we need to verify that
  - Gd-loaded water does not degrade the tank materials
  - The tank materials do not degrade the water

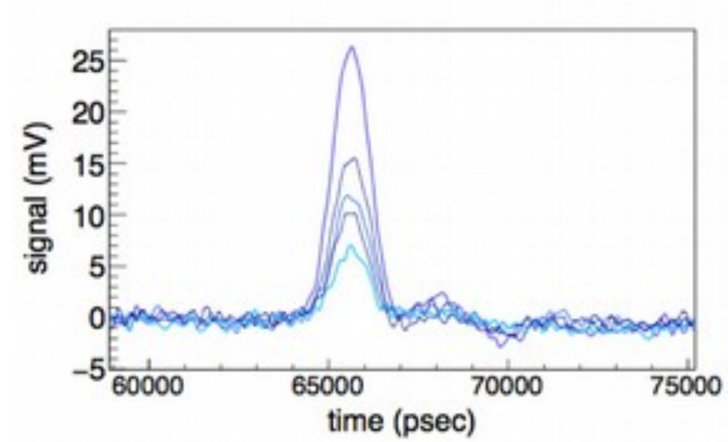
one month

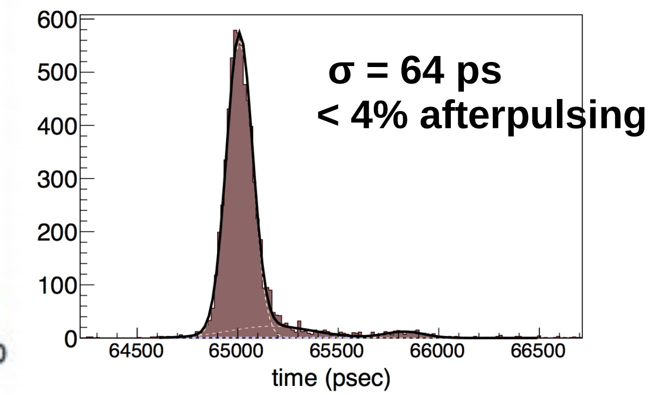


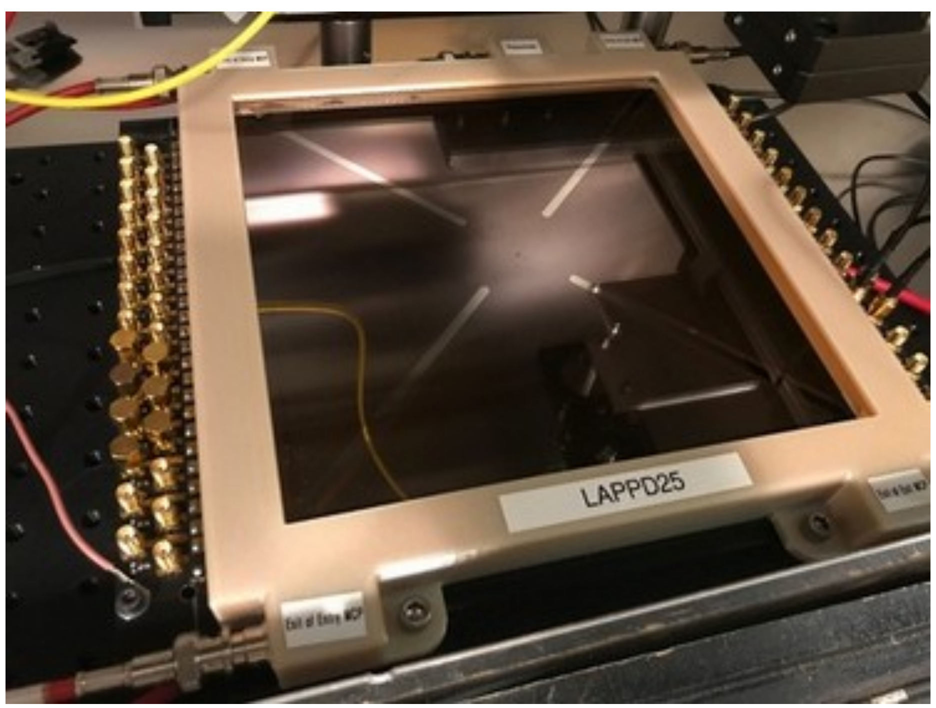
LAPPD testing is ongoing



Waveforms and transit time spread







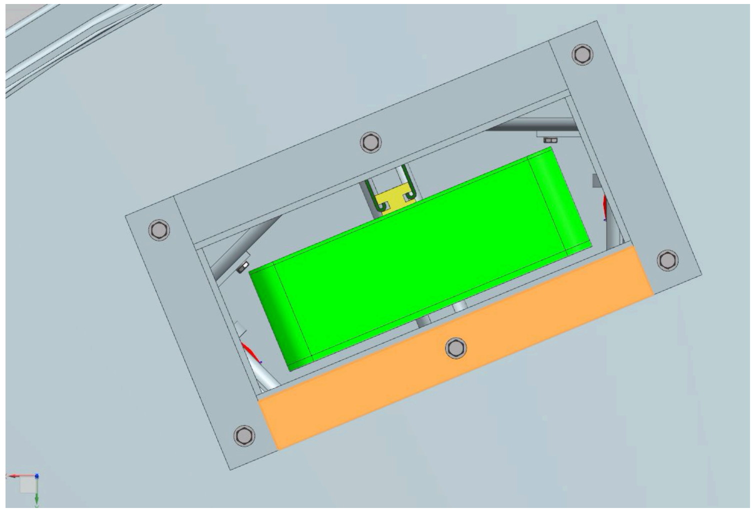
Dedicated LAPPD test stand

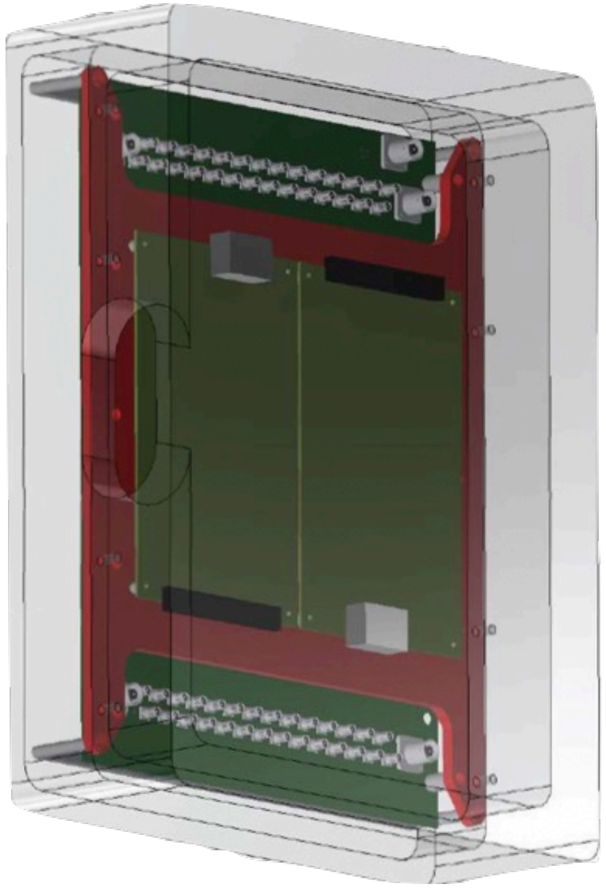
LAPPD 31 (our second!) before and after opening

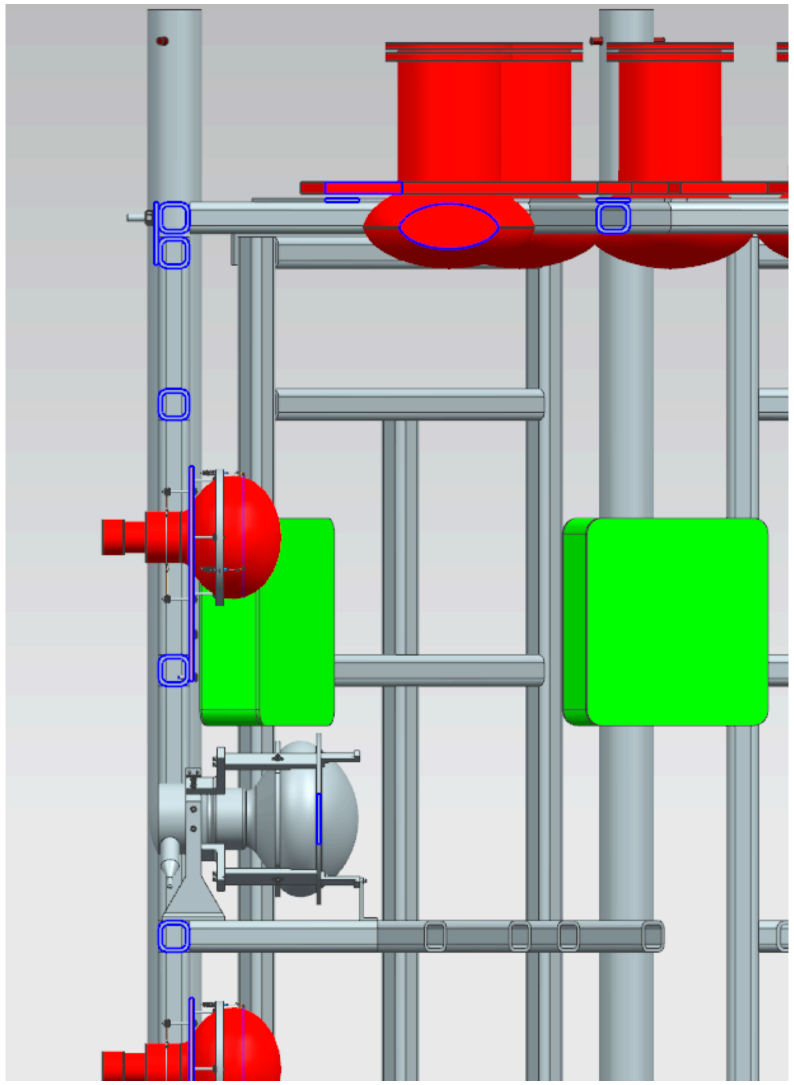
Fermilab

ANNIE design allows for easy installation of additional LAPPDs

- LAPPDs and the associated electronics will be installed in movable waterproof housings
- These housings will be lowered into the tank on rails accessible from the top hatch
- Installation and removal may be conveniently done by hand
- Phase II will begin with 5 LAPPDs, with room for many more







Future Plans

Timeline for Phase II and beyond

Pure water
Spring 2019

→ **Commissioning**

Gd-loaded water
Spring 2019 - Summer 2020

→ **Physics data taking**
→ Neutron yield measurement
→ CC cross section measurement
→ CC0π cross section measurement

Additional LAPPDs
Fall 2020

→ More detailed reconstruction of multi-track final states and pions
→ Possible NC cross section measurement

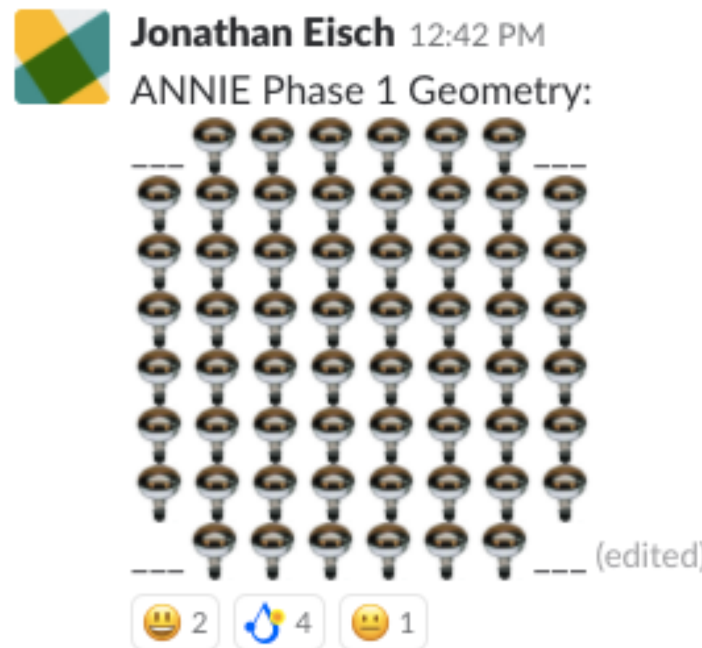
Phase III
2021 or 2022

→ **Testbed for new technologies**

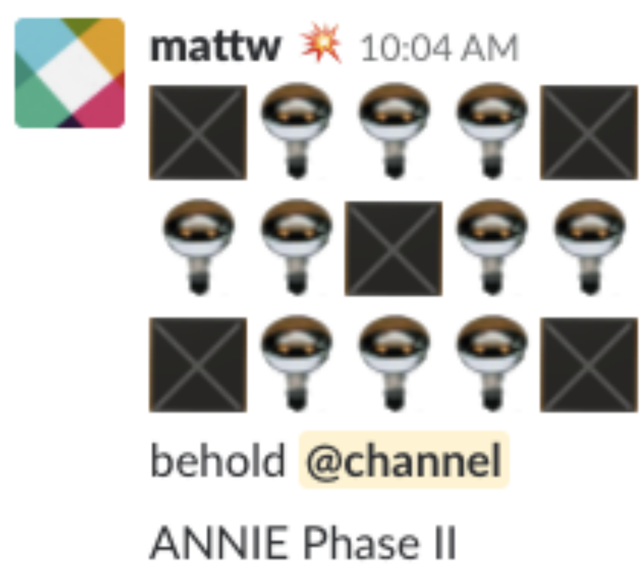
The ANNIE story in emoji

Invention of the PMT

Phase I



Phase II

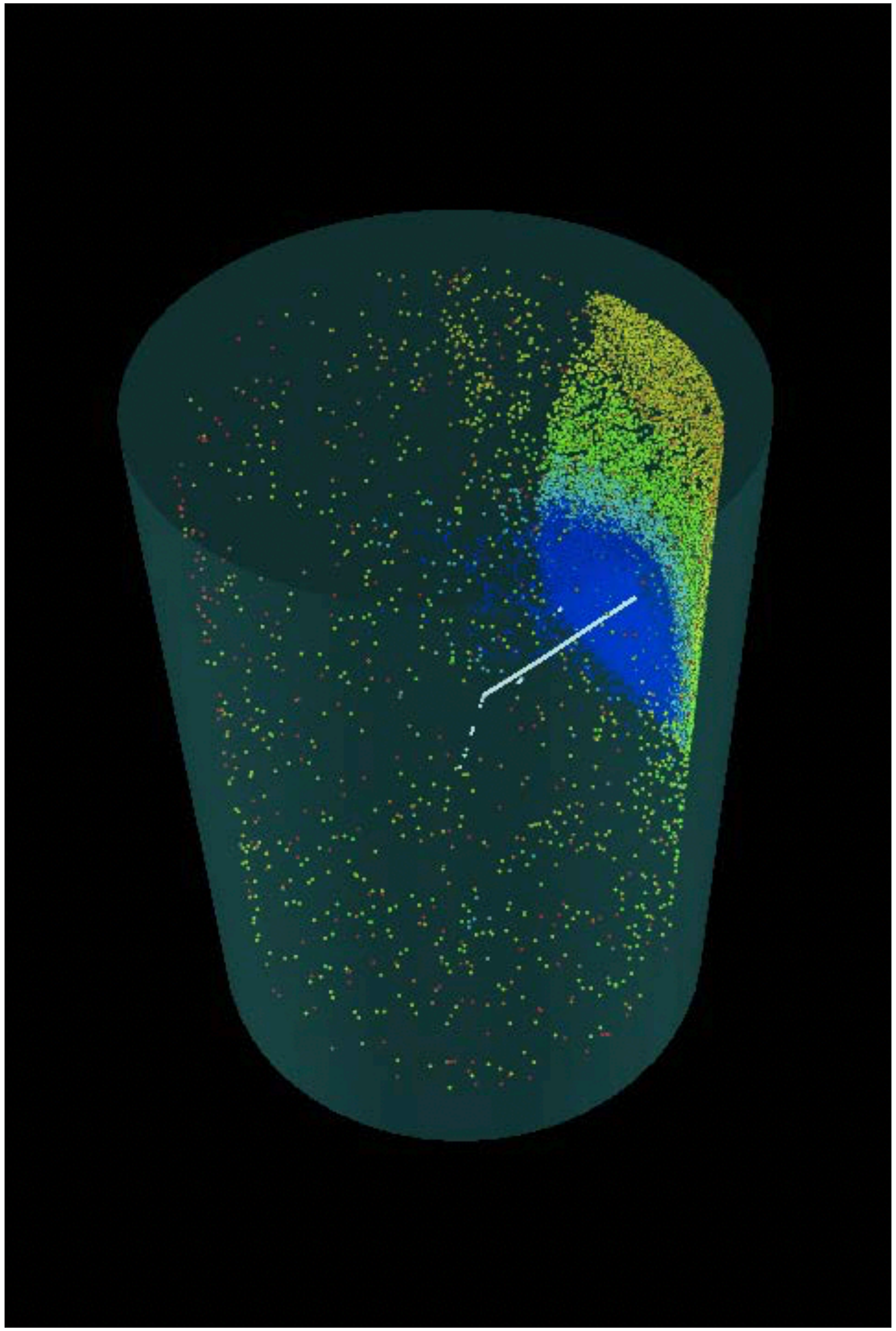


ANNIE Physics Program

- The primary physics analysis for Phase II of ANNIE is a **measurement of CC cross sections and neutron yields in bins of lepton kinematics**

- Obtaining this information for CCQE-like events (one muon, no other tracks) is particularly high-priority

- Further development of the detector capabilities has the potential to broaden the ANNIE physics program . . .



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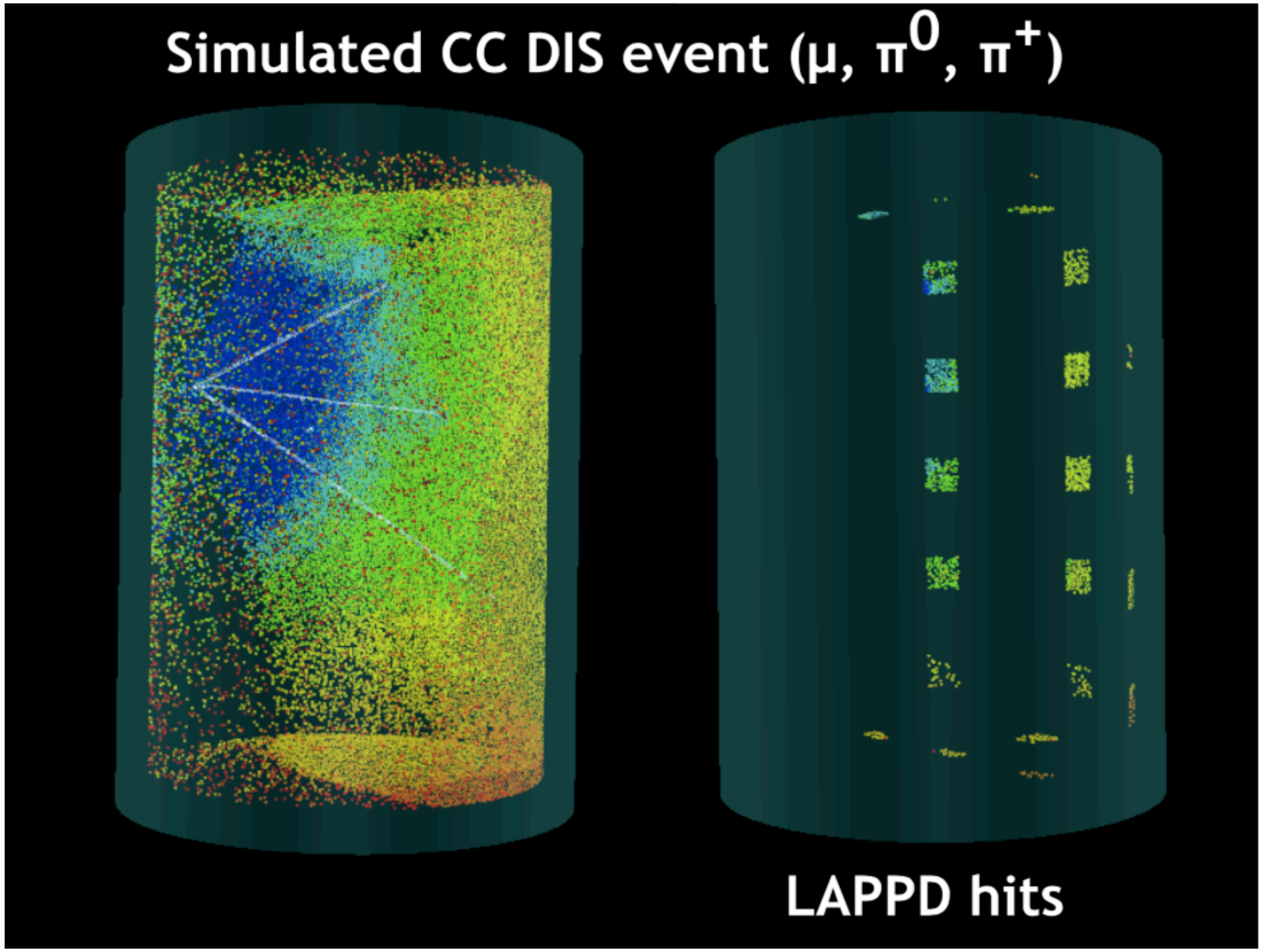
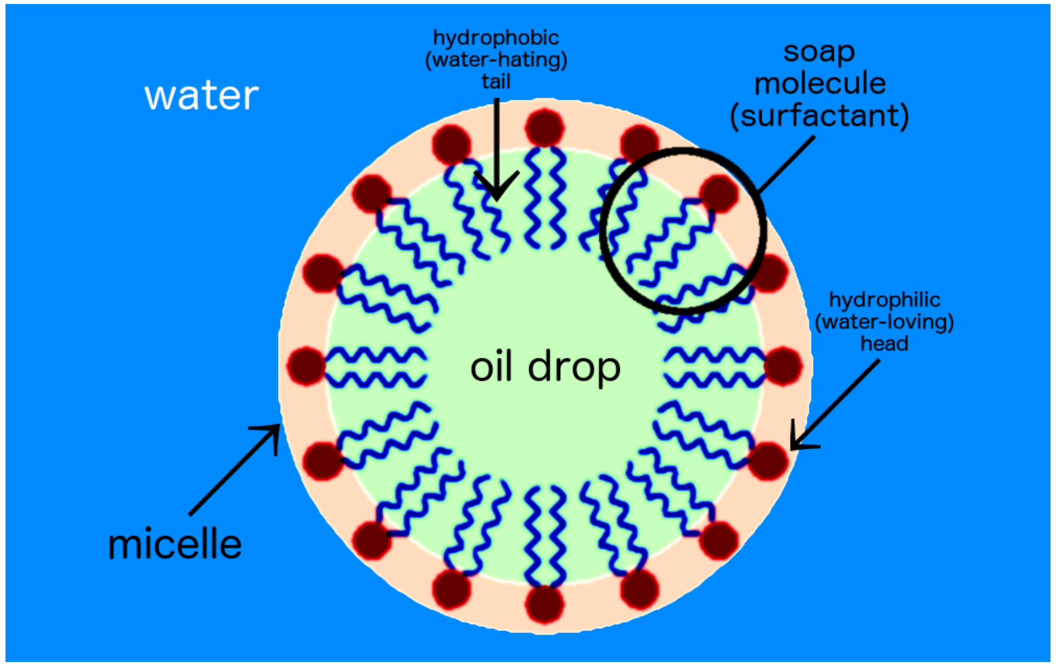
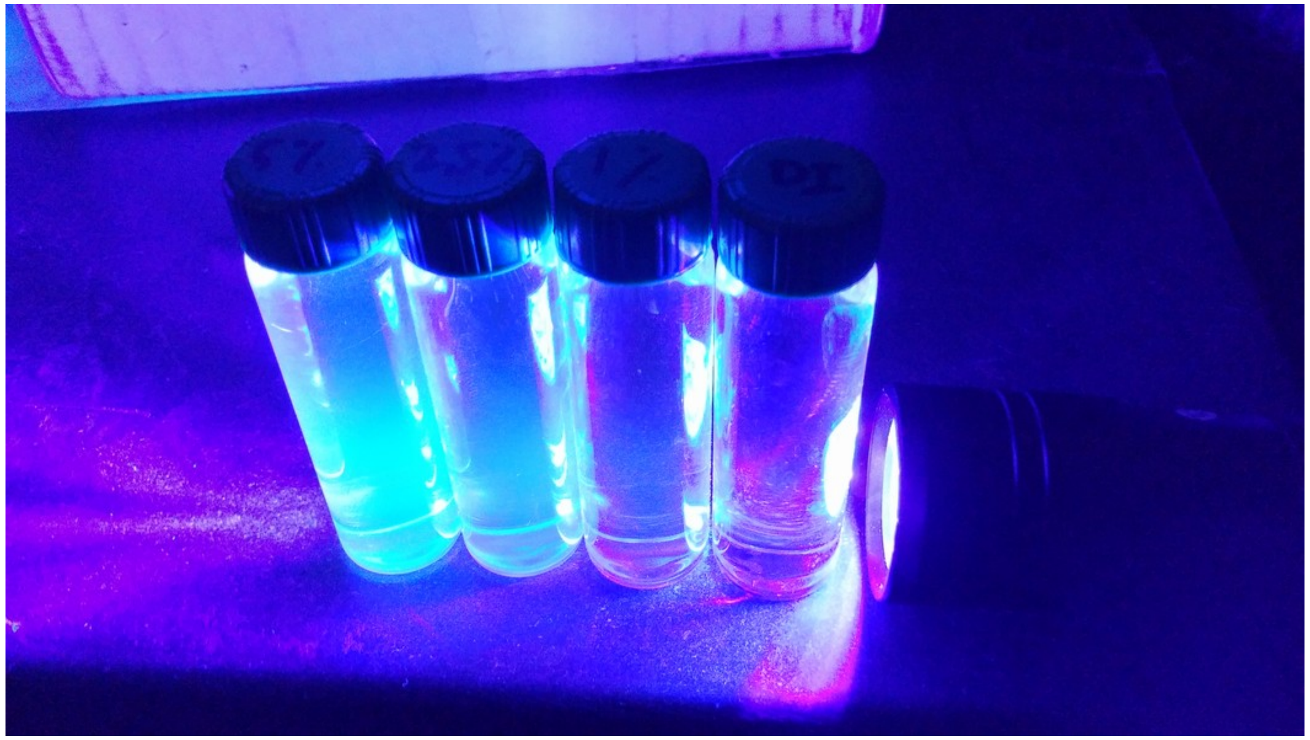


Water-based Liquid Scintillator (WbLS)

- Combination of pure water and hydrocarbon liquid scintillator
- **Water and oil don't mix, but we can cheat**: stable scintillator droplets (called micelles) can be formed in water using a surfactant!
- Combines the advantages of water (low light attenuation, low cost) and liquid scintillator (high light yield)
- Emission of **prompt Cherenkov** light and **delayed scintillation** light
- **Great flexibility**: tunable liquid scintillator concentration, isotope loading possible



micelle structure in water



samples of WbLS with different LS concentrations

Physics impact of WbLS

- Separating Cherenkov and scintillation light allows for **combined kinematic and calorimetric energy reconstruction**

- Fast timing capabilities of LAPPDs make this a viable strategy

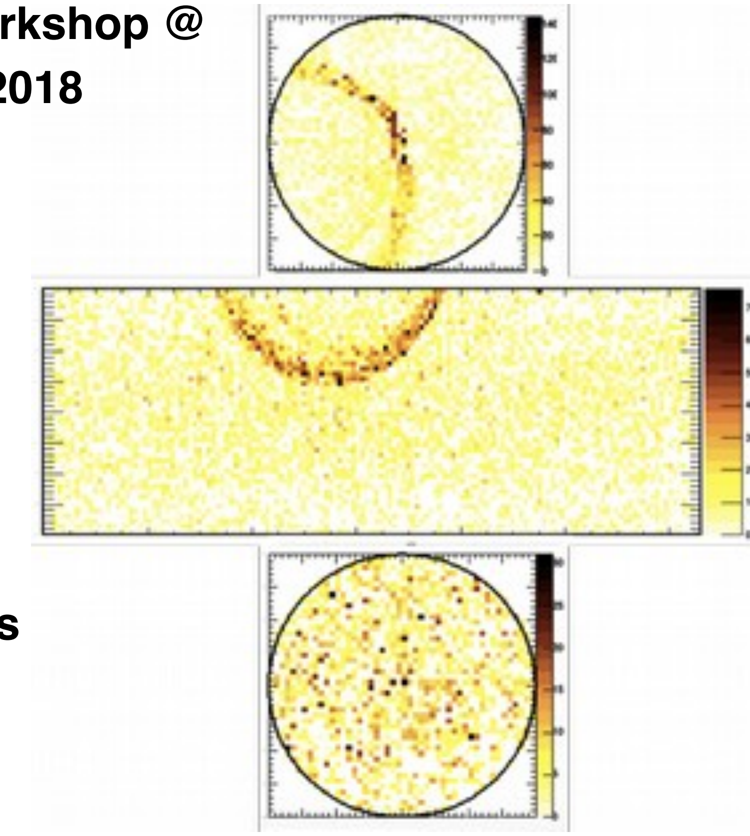
- Potential for **greatly expanded physics information**

  - Neutron capture vertex reconstruction

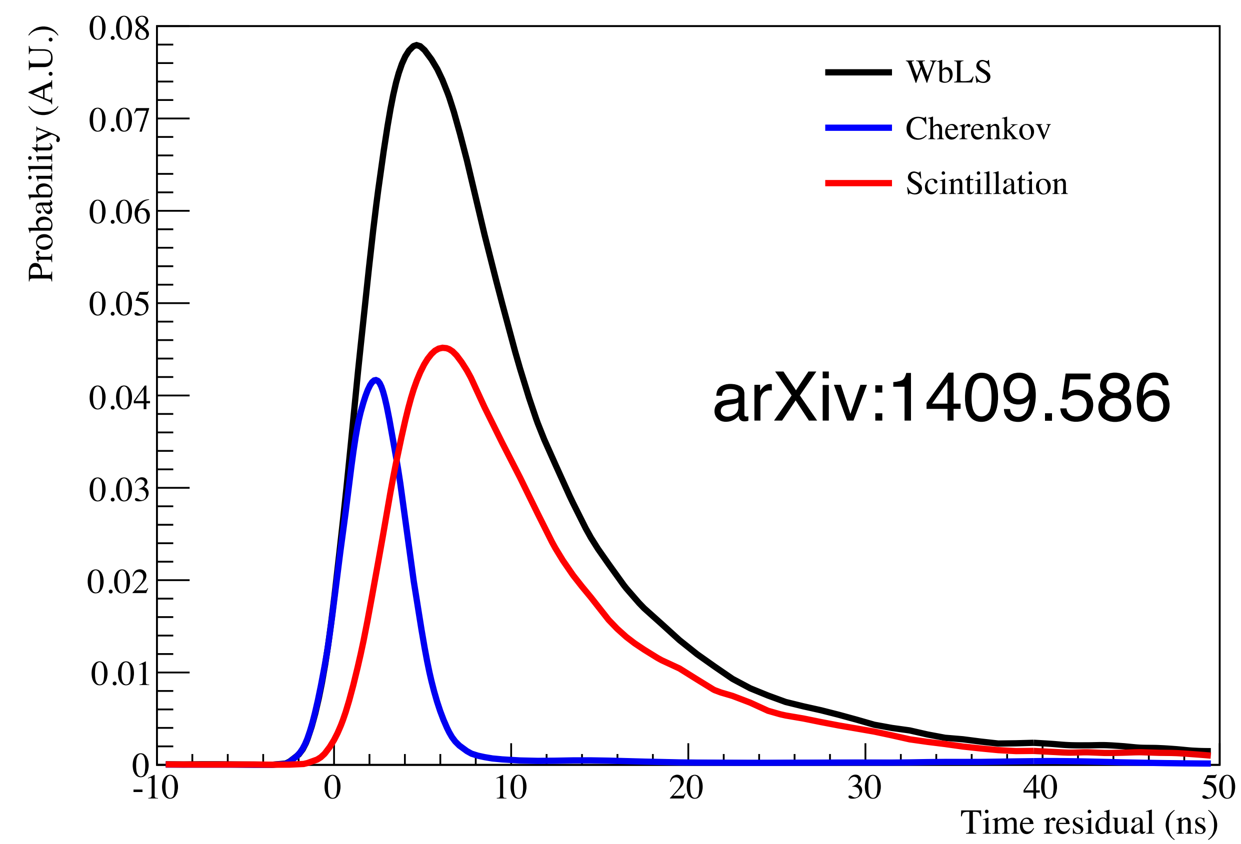
  - Charged particle detection below the Cherenkov threshold (protons?)

  - Low-energy activity (inelastic neutron scatters?)

L. Picard, Theia Workshop @ UC Davis, 12 April 2018



Simulated photon hits from a CCQE event in WbLS. The Cherenkov ring is clearly visible over the homogeneous scintillation light.



R&D for future large experiments: WATCHMAN

- 2 kiloton Gd-loaded water Cherenkov detector
- **Security mission**: demonstrate remote reactor monitoring via neutrino detection
- First experiment in the NNSA-sponsored Advanced Instrumentation Testbed (AIT)
- Interest in adding WbLS inner volume and/or LAPPDs
- Construction started October 1

R&D for future large experiments: Theia

- 50 kiloton detector filled with water-based liquid scintillator
- Reap the benefits of combined kinematic and calorimetric energy reconstruction in a large detector
- Plans for a broad physics program
  - Long baseline neutrinos
  - Neutrinoless double beta decay
  - CNO-cycle solar neutrinos
  - Geo-neutrinos
  - Supernova neutrinos

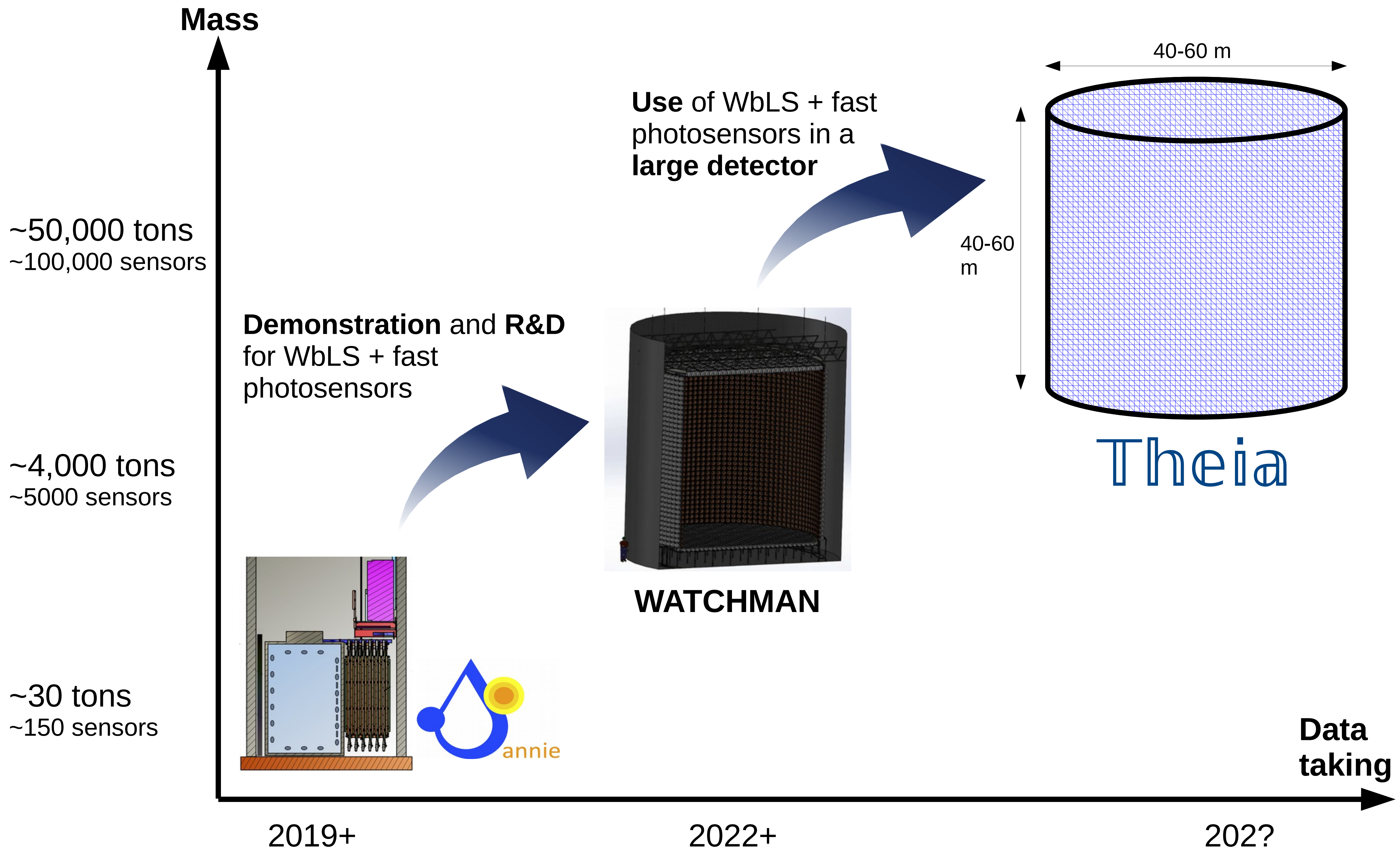
Theia Workshop @ Fermilab:

12-14 December 2018

Registration open at

https://indico.fnal.gov/event/18662/

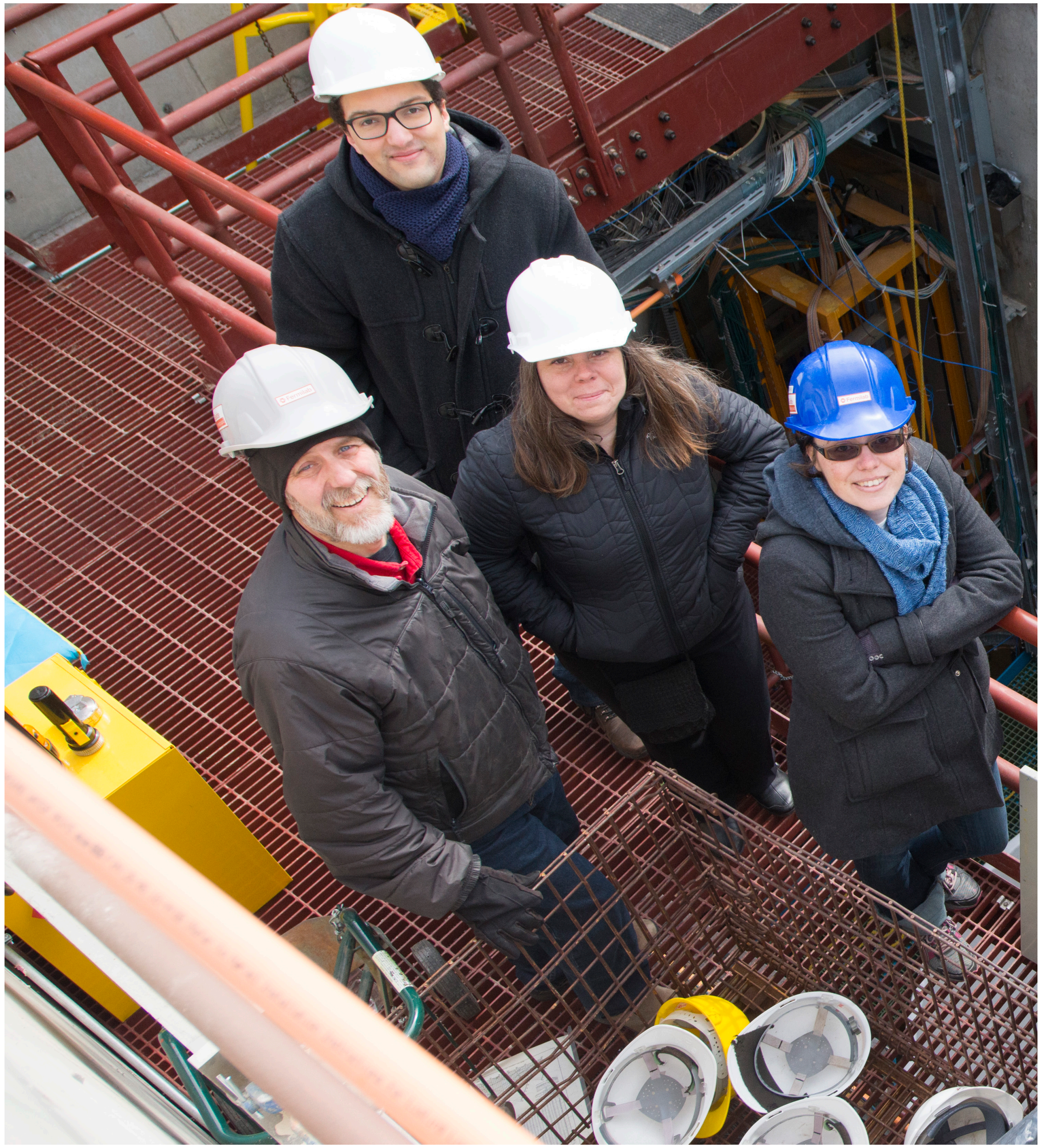
ANNIE → WATCHMAN → Theia



In memoriam: Bill Lee

The ANNIE collaboration would like to thank Bill for his invaluable help and leadership as our Experiment Liaison Officer.

He was essential in getting Phase I off the ground.



1965–2016

Thank you, Fermilab!

- Existing resources and facilities at Fermilab have greatly aided ANNIE to keep costs down while making rapid progress

- The collaboration would like to thank Jim Kilmer, Kurt J Krempetz, Geoff Savage, John Voirin and his Technical Crew., ND and PPD Divisions, PREP, and ESH&Q for their support!

Conclusion

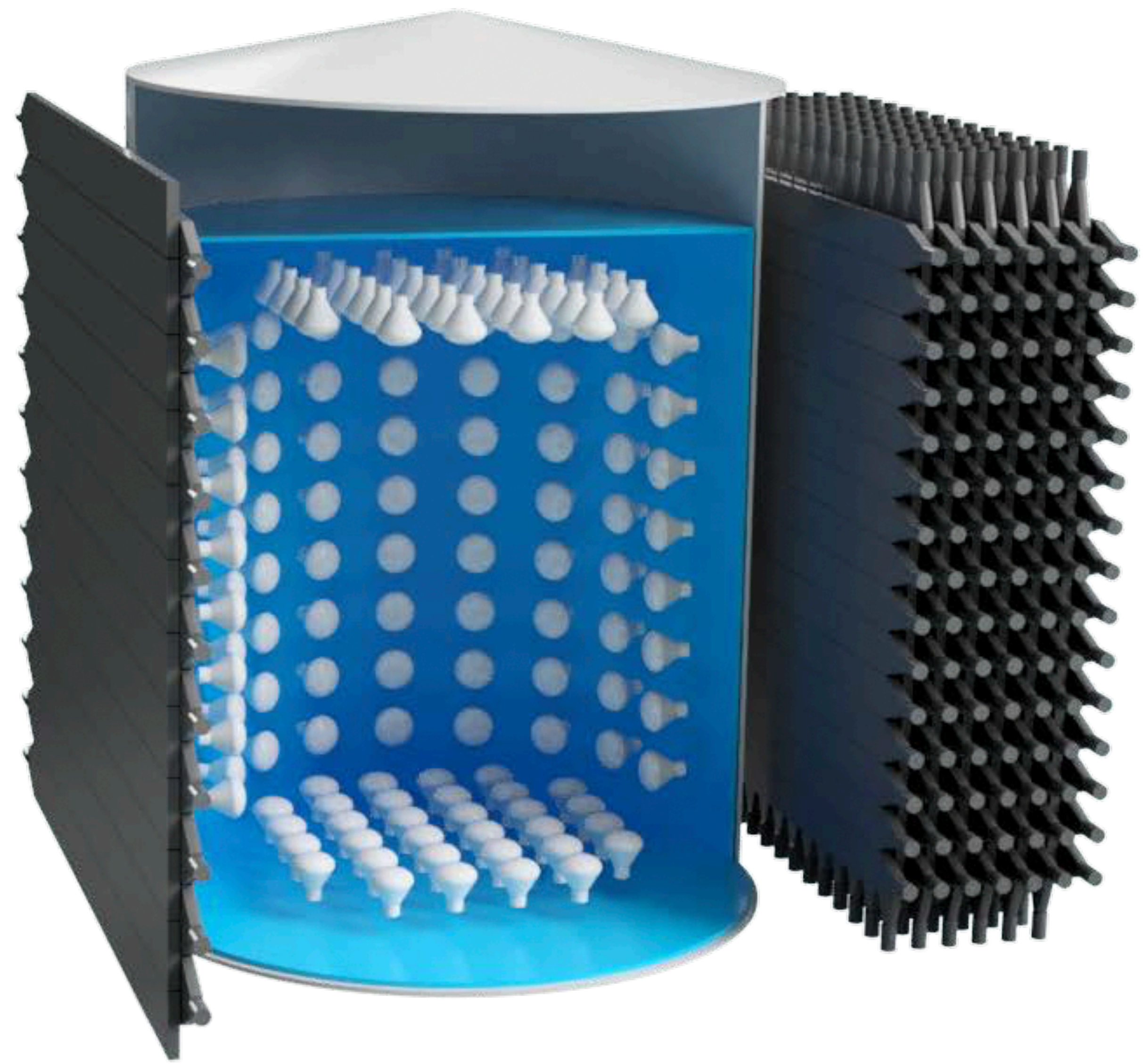
- The ANNIE experiment will measure neutrino-induced neutron yields to better constrain neutrino interaction uncertainties and enable powerful signal/background separation for rare event searches

- Phase I of the experiment is complete. Neutron backgrounds are sufficiently low for the physics measurements to proceed.

- Phase II is under construction, with first data expected this spring

- ANNIE is pleased to be a part of the Fermilab neutrino community! We look forward to continuing the journey of discovery with you.

  - New collaborators welcome!



Backup

LAPPD Price Projections

- Current costs are driven by overhead rates, non-reimbursed R&D Costs, and low volume
- Costs drop rapidly, as demand and volume increases.
- Incom projects price to drop from current levels as follows:

Timing	Cmrcl Price	DOE Price	Cum Vol.	Annual Capacity
Current	$ 75,000	$ 50,000	48	48
1	$ 56,250	$ 37,688	58	82
2	$ 45,000	$ 30,150	144	120
3	$ 36,900	$ 24,723	268	204
4	$ 31,365	$ 21,015	502	264
5	$ 30,032	$ 20,121	1,000	278

With full scale production, and cumulative volumes of product produced approaching 10,000 units, a price of $10,000 or less, for a full size LAPPD, is entirely plausible.

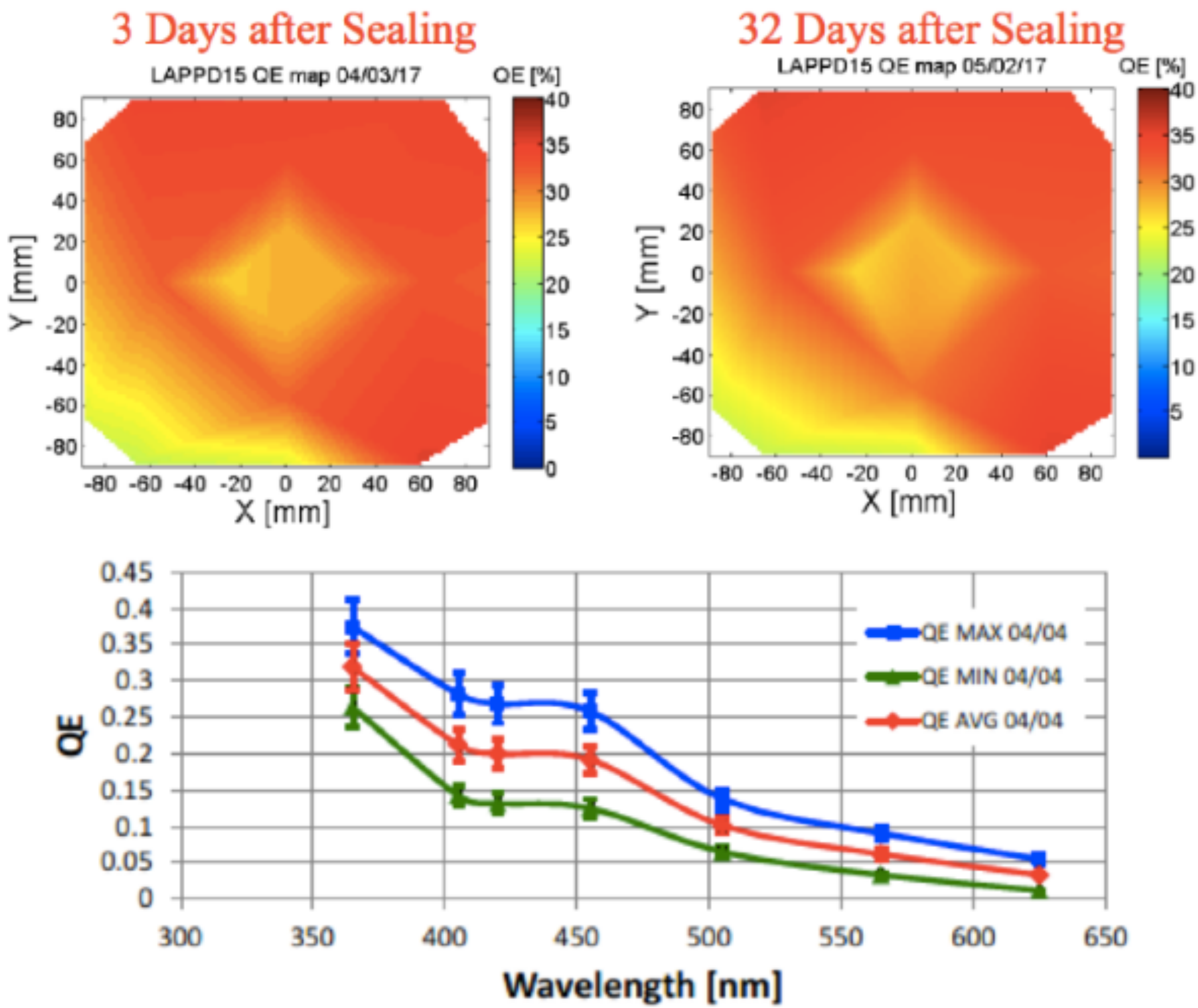
Thursday, Nov 15, 2018

LAPPD™ Early Adopter Programs

PI & SPONSOR	PROGRAM TITLE
Mayly Sanchez and Matthew Wetstein, Iowa State	ANNIE - Atmospheric Neutrino Neutron Interaction Experiment
Erik Brubaker, Sandia National Lab/CA	Neutron Imaging Camera
Graham Smith, Klaus Attenkofer (BNL)	Gamma & Neutron Detectors
Henry Frisch (U of Chicago) , Dmitri Denisov (Fermilab)	Precision Time-of-Flight with Commercial Photodetectors at the Fermilab Testbeam Facility
Matthew Malek,(u of Sheffield)	WATCHMAN, UK STFC
Josh Klein, U of Penn	Spectrally Sorting of Photons, using Dichroic Films and Winston Cones, WATCHMAN, THEIA
Gabrial D. Orebi Gann (UC Berkeley)	WATCHMAN, THEIA
Zein-eddine Meziani	High Rate Trials at Jefferson Labs, EIC
Andrey Elagin (U of Chicago)	Neutrino-less Double-Beta Decay
Mickey Chiu (BNL) -	Phenix Project - “eIC Fast TOF”
John Learned, U. of Hawaii, and Virginia Tech	Short Baseline Neutrino (NuLat)
Lindley Winslow (MIT)	Neutrino-less Double-Beta Decay (NuDot) Using Fast Timing Detectors
Andrew Brandt, (UT Arlington)	Life Testing of LAPPD

Thursday, Nov 15, 2018 LAPPD Performance Test Results - NSS MIC

Testing of LAPPD #15 at Incom



Modeling neutron production in neutrino interactions

Paola Sala, NuInt 2018

Nuclear interactions in FLUKA: the PEANUT model

Target nucleus description (density, Fermi motion, etc)

t (s)

~~Glauber-Gribov cascade with formation zone~~

10^{-23}

Generalized IntraNuclear cascade

10^{-22}

Preequilibrium stage with current exciton configuration and excitation energy
(all non-nucleons emitted/decayed + all nucleons below 30-100 MeV)

10^{-20}

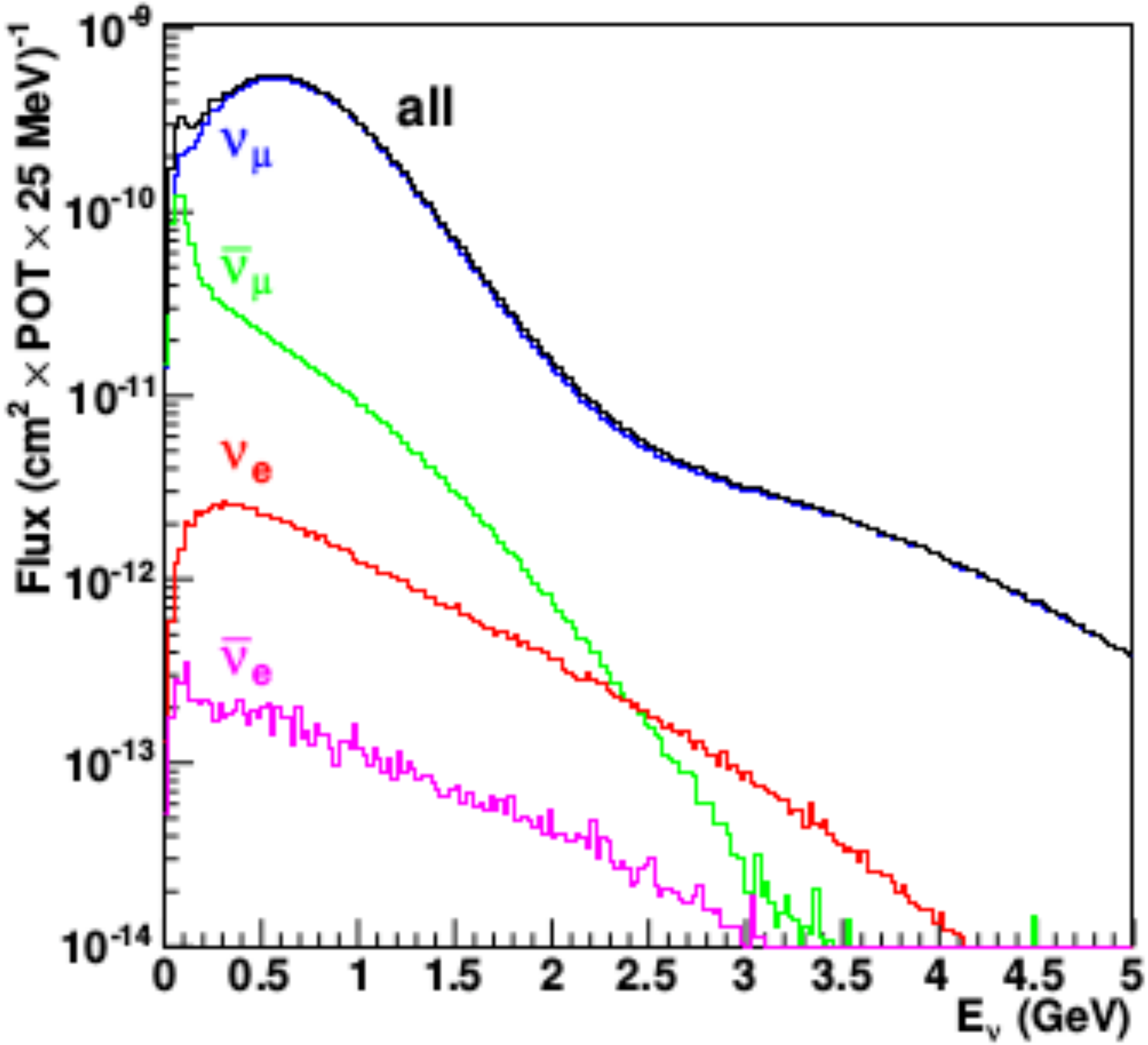
Evaporation/Fragmentation/Fission model

10^{-16}

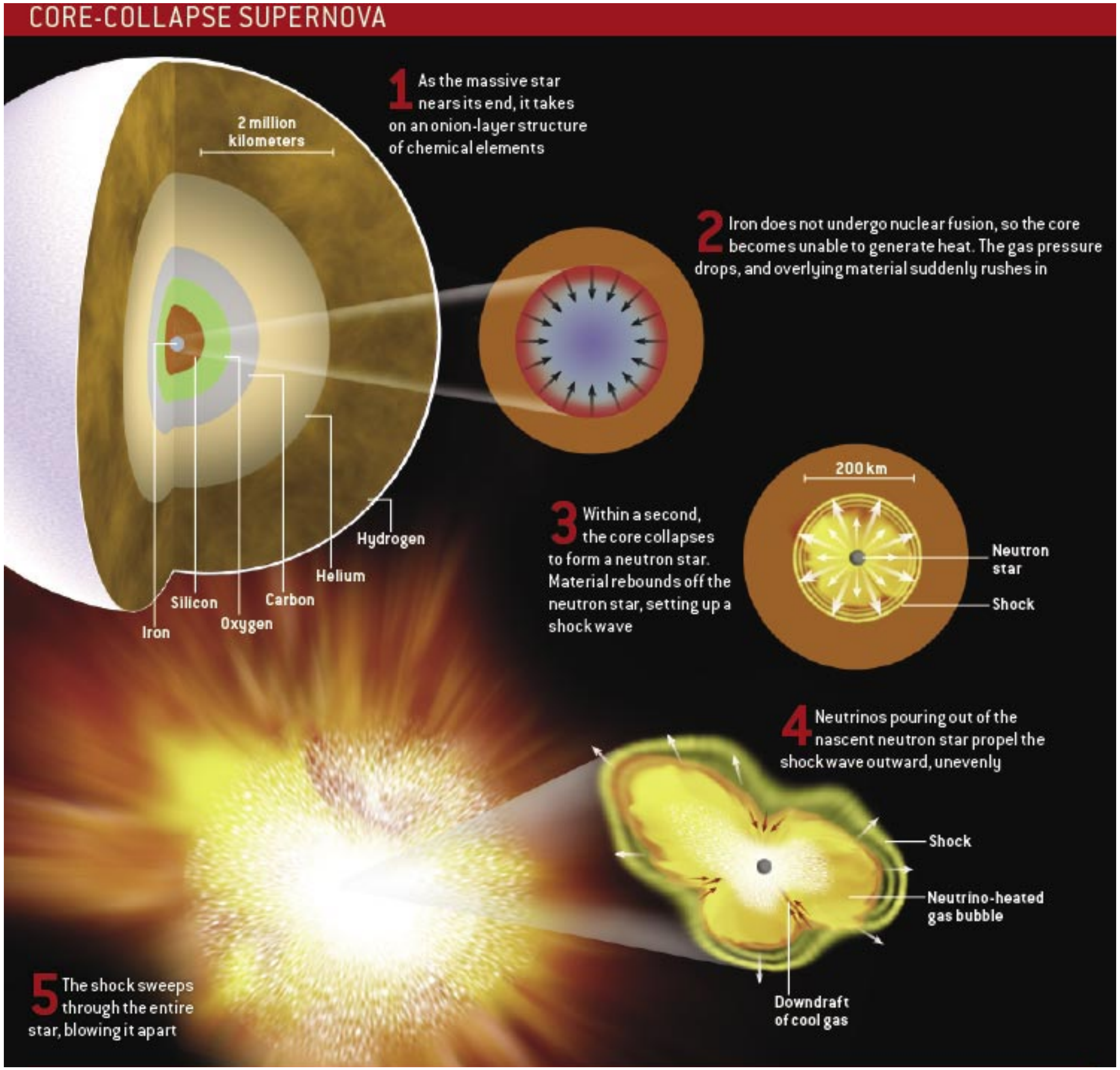
γ deexcitation

Oct 2018 NUINT 2018 15 15

Neutrino flux prediction at SciBooNE hall



Core-collapse supernovae: near-perfect neutrino bombs



- Deaths of stars > $9M_\odot$
- 99% of gravitational binding energy emitted as neutrinos
- Many ν_e produced as core collapses (few-ms burst)
- Core cools via all-flavor neutrino radiation in ~10s
- Momentarily outshines visible universe (in neutrinos)
- **Nearby supernovae are rare**. Last one seen in 1987.

Fermilab

Phase I systematics summary

- **NCV efficiency** (dominant, 22.4%)
  - Estimated using difference between ^{252}Cf and cosmic ray calibration methods
  - We can likely do better in Phase II with a well-understood neutron source (AmBe)
- **POT normalization** (2%)
  - Nominal spread between the two beam current toroids found in routine calibrations
- **NCV liquid volume** (5.7%)
  - Conservative errors on the inner NCV dimensions (might not be quite full)
- **Event counts** (varies with position, typically a few percent)
  - Afterpulsing (can't tell captures from afterpulses soon after proton recoils)
  - NCV containment
  - Accidental cosmic ray vetos

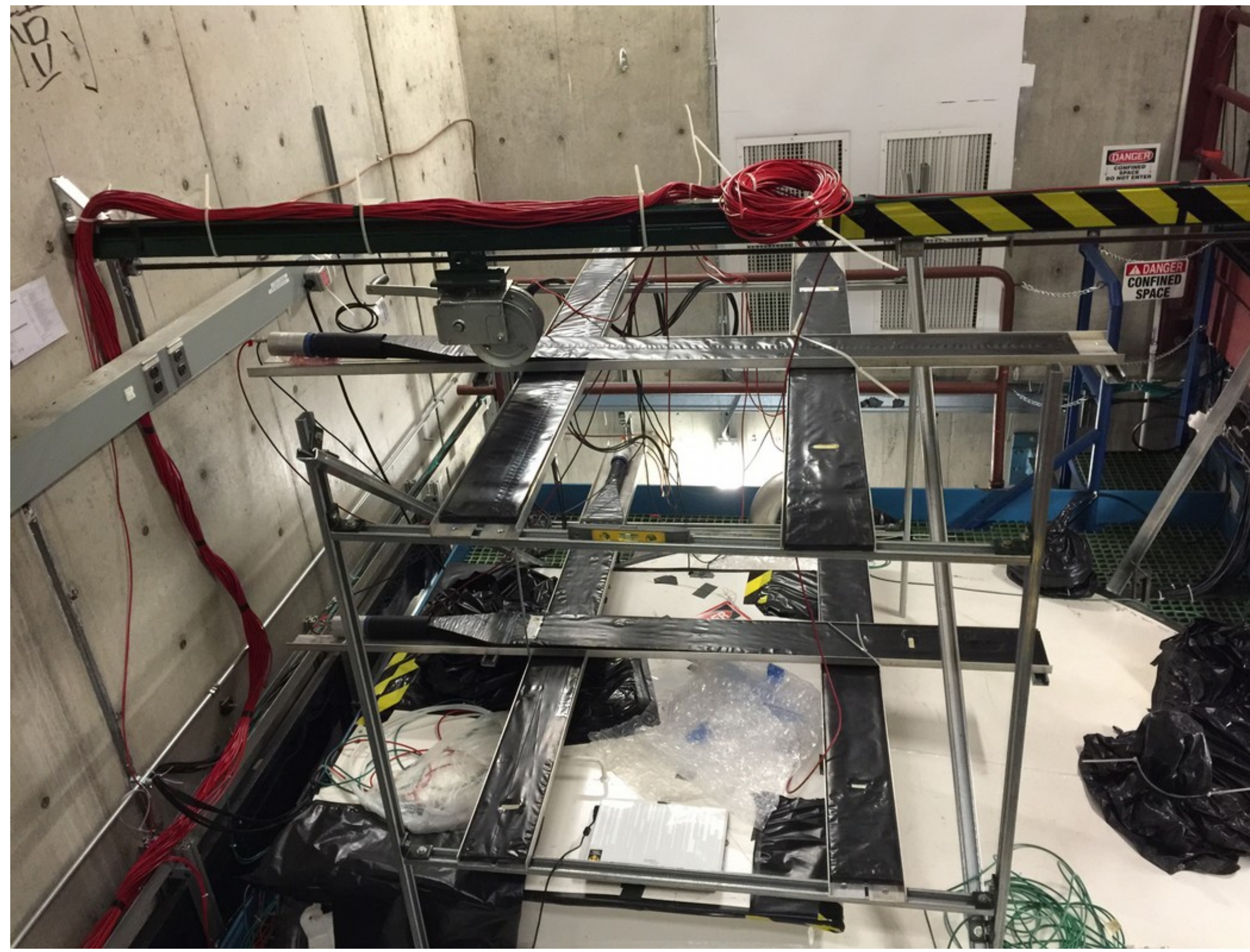
Cosmic muon trigger

- 6 scintillator paddles borrowed from DUNE 35 ton prototype
(thanks, Stephen Pordes!)

- Used for testing and calibrations

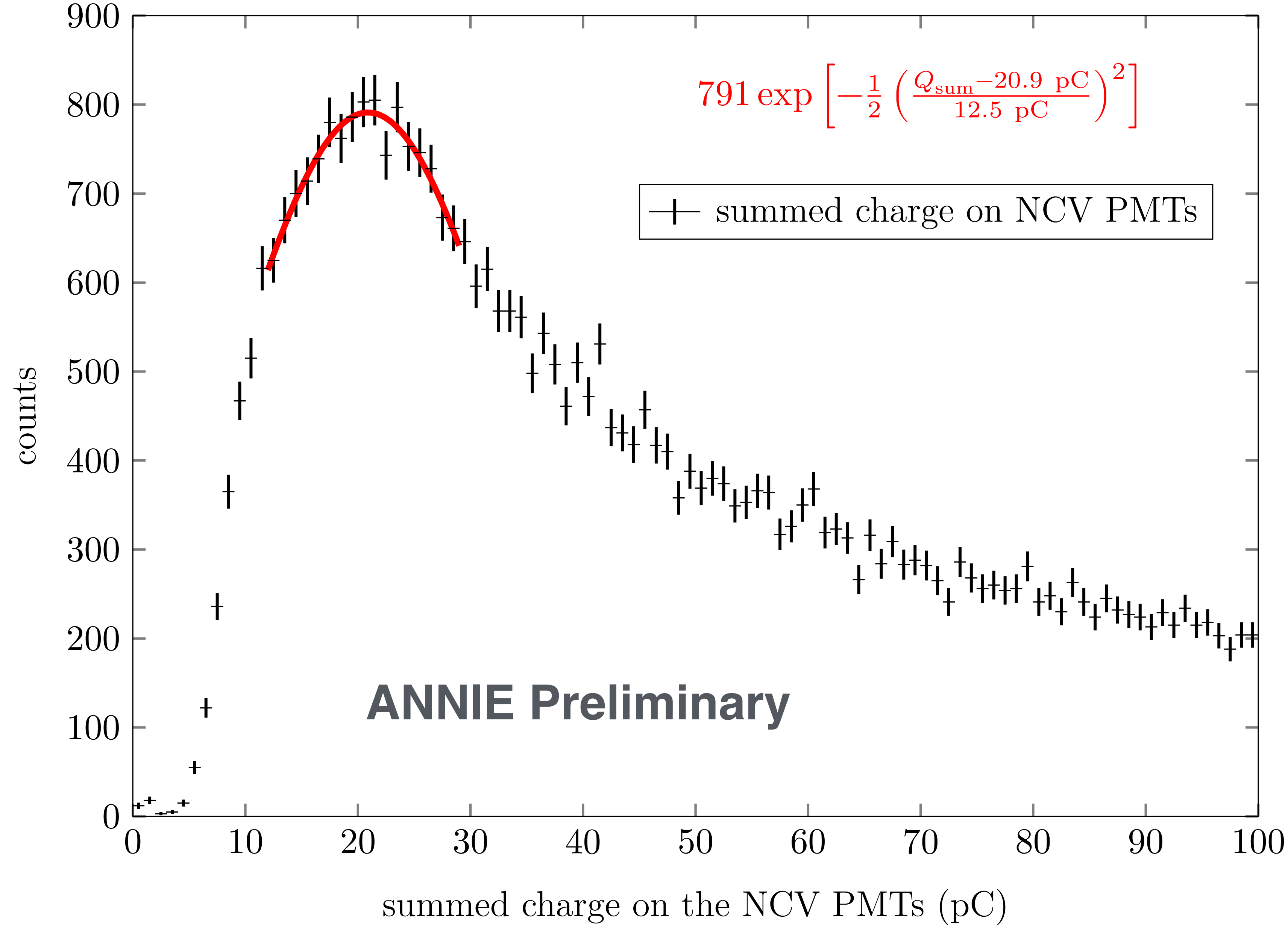
- Allowed the Phase I ANNIE detector to be triggered on vertical or 45° muons

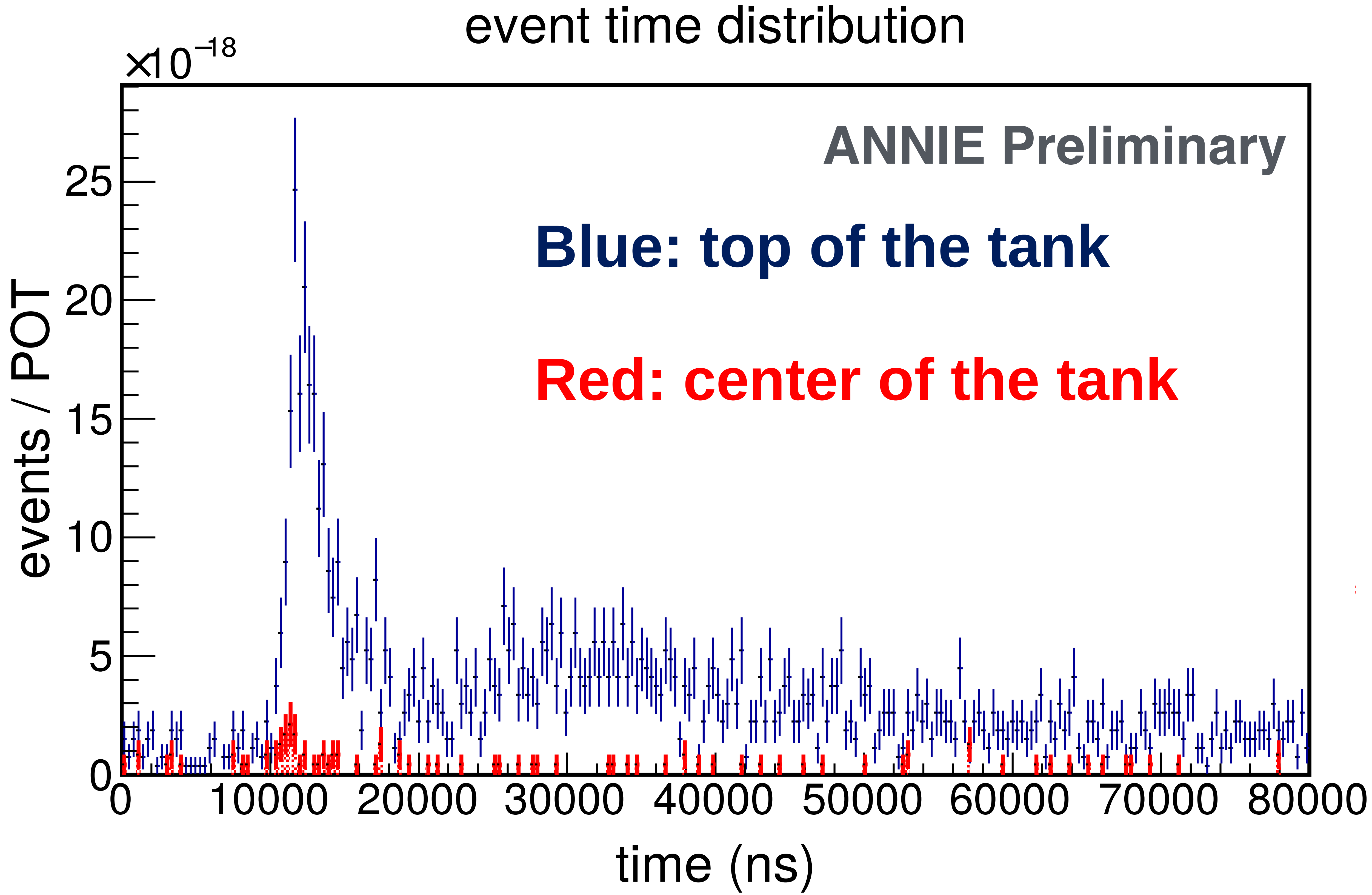
- Select tracks passing through the NCV or through the water outside the NCV



NCV calibration: cosmic ray method

- Cosmic muons passing through the NCV were selected using the cosmic ray trigger
- These data were compared to MC to obtain a charge-to-energy conversion factor
- Used to convert mean charge at threshold to an energy threshold
- Efficiency estimated using the fraction of simulated neutron captures that deposited energy above this threshold




event time distribution
×10^-18
ANNIE Preliminary
Blue: top of the tank
Red: center of the tank
events / POT
25
20
15
10
5
0
0
10000
20000
30000
40000
50000
60000
70000
80000
time (ns)

NCV calibration: cosmic ray method

- Cosmic muons passing through the NCV were selected using the cosmic ray trigger
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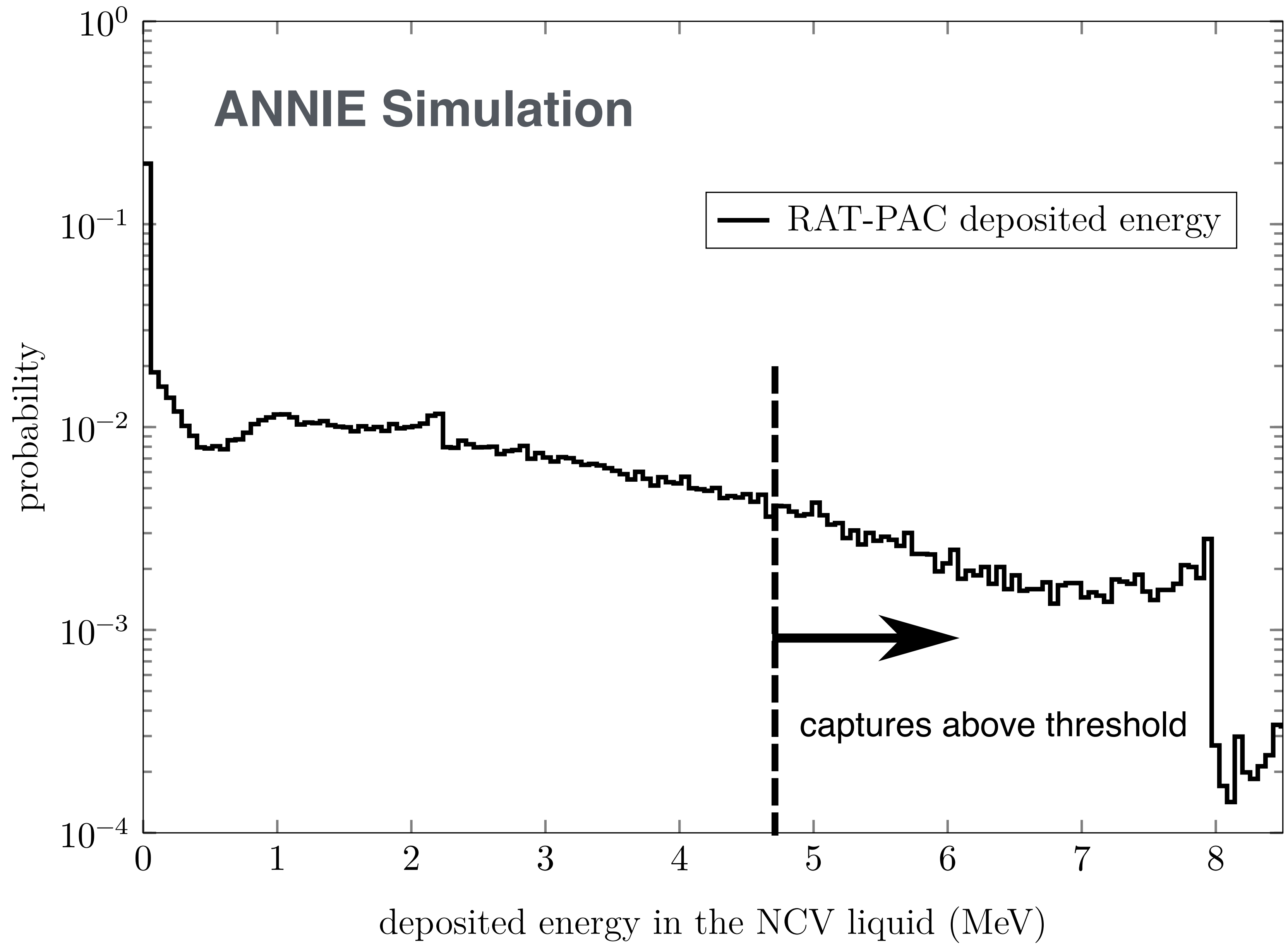


^{252}Cf source efficiency result: **9.60 ± 0.57(stat)%**

Cosmic efficiency result: **12.8 ± 0.9(stat)%**

Cosmic ray trigger data: demonstration of muon cuts

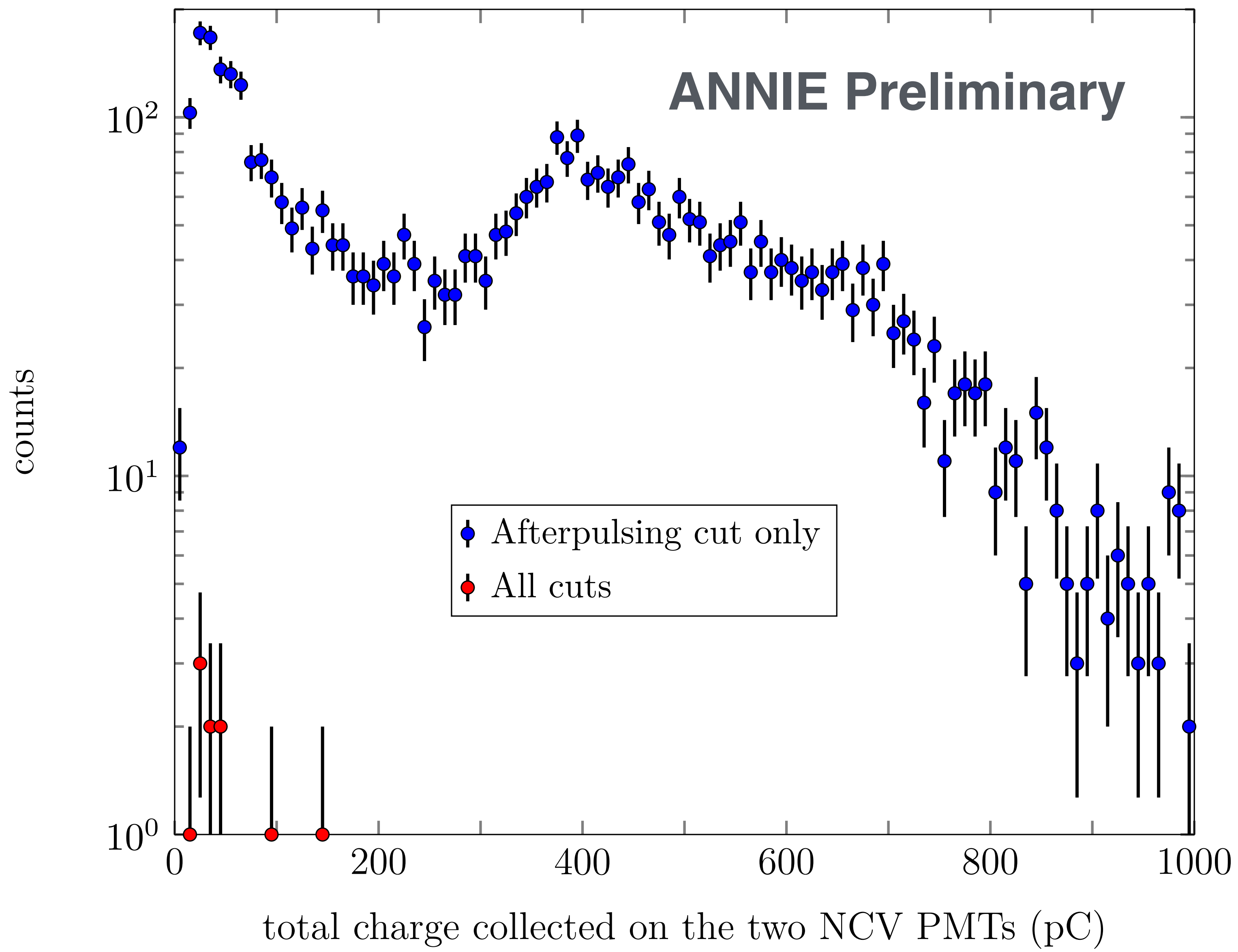
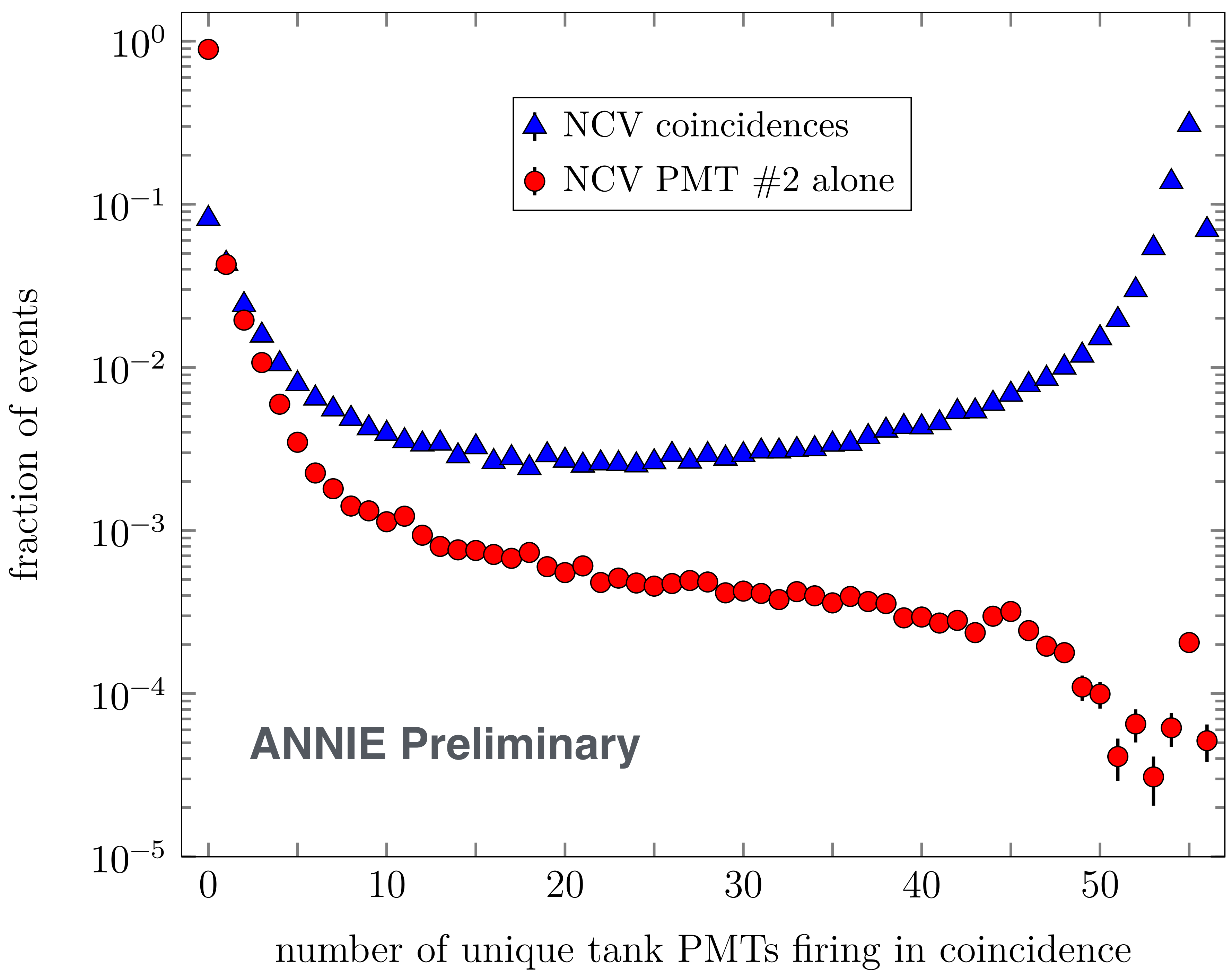


Figure 9.5: **BLUE**: Distribution of the total charge collected on both NCV PMTs for NCV coincidence events that passed the afterpulsing cut. All events shown here were recorded within 2 μs of a cosmic trigger consistent with a downward muon passing through the NCV. **RED**: The corresponding charge distribution when all neutron candidate event cuts have been applied.

Tank activity for NCV events



Fermilab

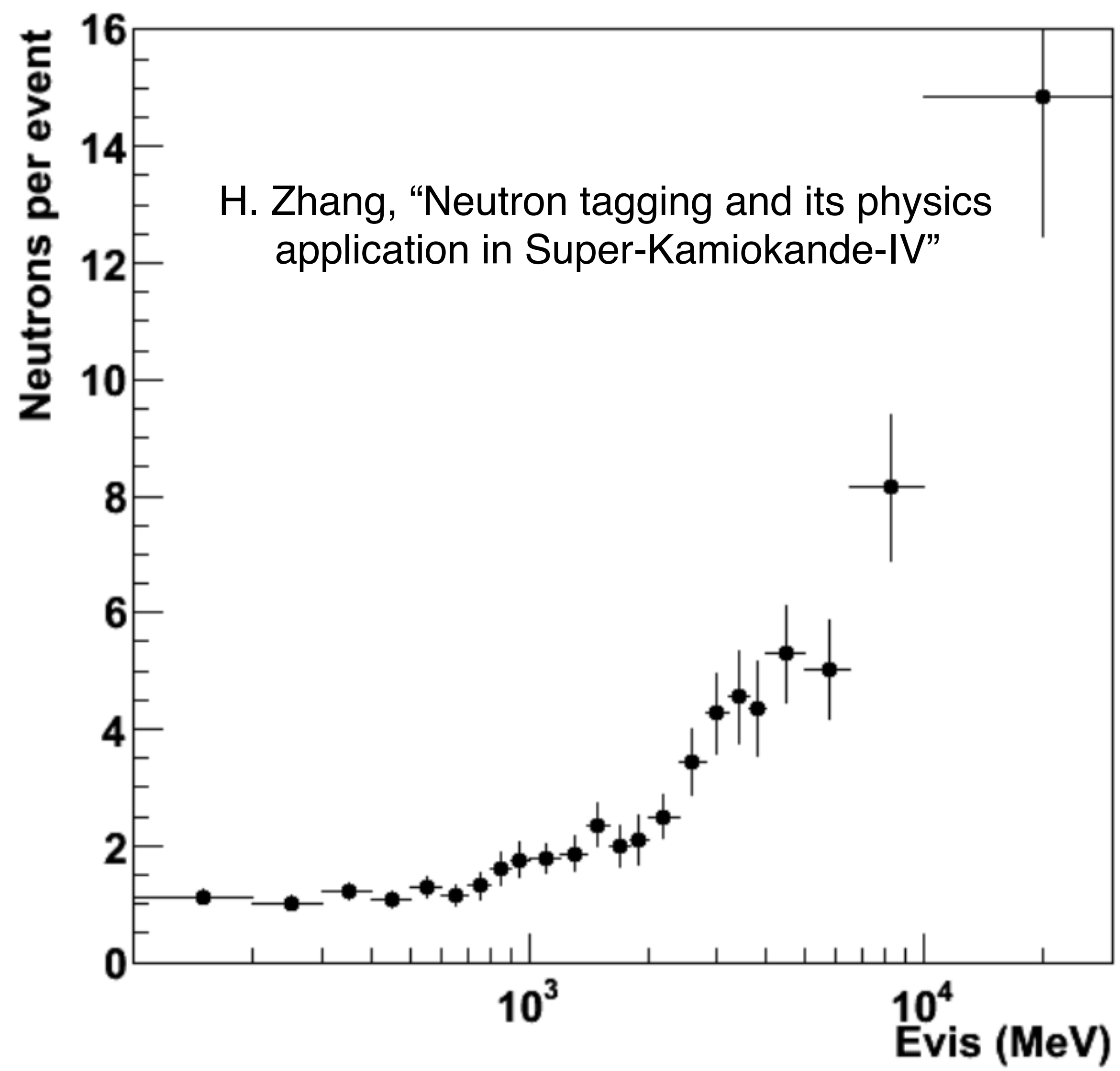
Haven't we already seen neutrino-induced neutrons in water?

- Super-Kamiokande recently performed a measurement of the neutron yield from atmospheric neutrino scattering as a function of visible energy

- **Some limitations**:
  - Only visible energy (no detailed kinematic information)
  - Unknown neutrino flavor and interaction type
  - Pure water gives a **low detection efficiency** (17%)

- ANNIE's more detailed measurement will require a high neutron detection efficiency

- **Gd loading will be crucial to achieve ANNIE's physics goals**



Super-K Gd recirculation system would be a bit much for ANNIE . . .